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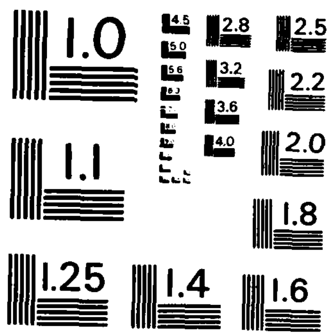

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ABSTRACT

The research done in this thesis is focused on the problem of reducing electrostatic unbalances that are inherent in transmission lines. The solution is threefold and will be presented in that fashion. First, the unbalance can be modified by varying the conductor size. Secondly, an unbalance can be reduced by adding ground wires. Lastly, the unbalances can be changed by rearranging the phase sequence.

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ELECTROSTATIC UNBALANCES OF TRANSMISSION LINES

A Thesis Presented to the
Faculty of the Graduate School
University of Missouri-Columbia

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Joseph Nowikowski

Dr. Turan Gonen Thesis Advisor

August 1985

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The research done in this thesis is focused on the problem of reducing electrostatic unbalances that are inherent in transmission lines. The solution is threefold and will be presented in that fashion. First, the unbalance can be modified by varying the conductor size. Secondly, an unbalance can be reduced by adding ground wires. Lastly, the unbalances can be changed by rearranging the phase sequence.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Electrostatic unbalances occur in transmission lines and are of two types: zero sequence and negative sequence. The purpose of this research is to explore more fully what is already known about these unbalances. Work has been done in the past, particularly the 1950's, in the area of electrostaic unbalances but not in the depth covered here. One of the main factors limiting most past research was the absence of the high speed computer. Without the computer, researchers were not able to investigate the amount of material and cases that are possible today. As a result, details about unbalances were left unknown or had to be extrapolated based on a small sample.

1.2 Past Studies

Chapter 2 of the work reviews the major research done that involves electrostatic unbalances. Some sources date back to the early 1950's when the study was first emerging. Some trends were developed by these early pioneers and are explained fully in the chapter. It will be shown by this work that those trends are in fact accurate.

1.3 The Model

Chapter 3 deals with the actual model that will be used to calculate an unbalance. Anderson [4] is a main source of information in the development of this model. His ideas and equations were applied to some basic circuits and then studied. The circuits studied are both horizontal and vertical in geometry, single and double in complexity, with and without ground wires.

The theory behind the development of the model is contained in Chapter 3 The actual analysis of a real circuit is done in Chapter 4.

1.4 Cases Studied

This study can be broken into three main groups with some overlapping. One main area of study is the effect of varying conductor size on electrostatic unbalances. To do this part of the study, 27 different ACSR Aluminum Conductor Steel Reinforced (ACSR) conductors. will be tried on a variety of circuits. A second area of study is the effect of overhead ground wires (OHGW) on an unbalance. Circuits with none, one, two, three, and five ground wires will be tested. A four wire case was omitted for two reasons: a trend could be charted without a four ground case, and a four ground wire case is not commonly used. Some overlapping occurs in that all 27 wire sizes will be analyzed in the multiground systems.

The last area studied is that of rotating and twisting phase conductors. Partial transposition has an effect on electrostatic unbalances and its effect will be explained. When circuits were mathematically transposed or twisted only one conductor size was tested. The reason for only one conductor size is that the twisting effects the unbalances much more than the wire size. As a result, the changing of wire size would not be a factor.

CHAPTER 2

THE REVIEW OF LITERATURE

2.1 Introduction

Most of the research done in the area of electrostatic unbalances of transmission lines has occurred in the 1950's. However, during that period, the digital computer was not available. Therefore, much of the work lacks the required completeness, but a foundation was laid and the significant theory was developed by Gross [1] Weston [1], McNutt [2] and others [3-9].

Before any phase configurations or circuit designs can be discussed some basic groundwork is necessary. The very nature of what an electrostatic unbalance is must be considered. Also, the effect an unbalance has on a transmission line should be reviewed. After this introduction, it is possible to derive unbalance equations with a better understanding.

2.2 Background of Unbalances

According to Gross [1], "Electrostatic effects occur under all conditions of operation and are essentially independent of the load currents in the phase wires." To understand unbalances it is necessary to review some fundamental principles.

According to circuit theory, a capacitance develops between parallel plates of applied voltage [3]. This model can be applied to transmission lines. In transmission lines two types of capacitances are set up, capacitance between the conductors and capacitance to ground [1]. These capacitances induce charging currents and the charging currents, as well as other currents, are the basis for the unbalance factors.

Using symmetrical component analysis, currents and voltages can be separated into positive, negative, and zero sequence components [4]. Charging current is no exception. It too, has a positive, negative, and zero component. The separation of sequence components of the charging current is just one method of solving an unbalance factor. Other methods of solution involve the use of capacitances and potential coefficients [5].

2.3 Sequence Charging Currents Due to Capacitive Unbalances

Sequence charging currents in terms of the positive, negative, and zero sequence currents can be derived using capacitive unbalance analysis. These currents can then be used to calculate the two different electrostatic unbalances.

The derivation of the sequence currents is not as important as the final form. The purpose of this chapter is to review what research has been done. Interested readers are referred to the paper "Determination of Inductive and

Capacitive Unbalances for Untransposed Transmission Lines" by R. F. Lawrence and D. J. Povejsil [5] for a complete derivation.

Again, the potential coefficients are important and through system geometry a potential matrix can be formed. Lawrence and Povejsil [5] show how this matrix and a charge matrix can be manipulated into a form involving current, impedance, and voltage [5].

$$V_a=Z_{aa}I_a+Z_{ab}I_b+\ldots Z_{an}I_n \qquad (2.1)$$

$$V_b=Z_{ba}I_a+Z_{bb}I_b+\ldots Z_{bn}I_n \qquad (2.2)$$

$$\vdots \qquad\qquad \vdots$$

$$V_n=Z_{na}I_a+Z_{nb}I_b+\ldots Z_{nn}I_n \qquad (2.3)$$

The "Z" terms are what make up the impedance matrix of the transmission line. Subscripts a, b, and n represent individual phases. Obviously, if this impedance matrix were known, equations (2.1) through (2.3) would be easily solved.

Through successive mathematical manipulations, equations one through three can be broken up into sequence currents [5].

$$I_{a2}=-I_{a1}\frac{Z_{21}}{Z_{22}}=-I_{a1}\frac{P_{21}}{P_{22}} \qquad (2.4)$$

$$I_{a0}=-I_{a1}\frac{Z_{01}}{Z_{00}}=-I_{a1}\frac{P_{01}}{P_{00}} \tag{2.5}$$

Of course, these equations assume the positive sequence charging current is known. In fact, the current is straightforward to calculate. Assuming unity power factor, sequence current can be

$$I_{a1}=\frac{MVA}{\sqrt{3}\ kV} \tag{2.6}$$

if the MVA and kV are known in the circuit parameters [5].

Once all three charging sequence currents are known, it is possible to directly calculate all unbalances of the electrostatic nature. However, other methods also exist for these same calculations.

2.4 Unbalances to Ground

For a given three phase system an unbalance can be calculated one of two ways depending on whether the system is grounded or not. If grounded, the unbalance, d , is equal to the ratio of the magnitude of the neutral displacement voltage to the magnitude of the line to neutral voltage [2].

$$d_0=\frac{|V_0|}{|V_{1n}|} \tag{2.7}$$

If grounded, the unbalance factor is equal to the ratio of the unbalance current to the ground fault current [2].

$$d_0 = \frac{|I_u|}{|I_{gf}|} \tag{2.8}$$

However, d_0 can be calculated for either a grounded or ungrounded system using the following equation [2]:

$$d_0 = \frac{|V_0|}{|V_{1n}|} = \frac{|I_u|}{|I_{gf}|} \tag{2.9}$$

Where: $I_{gf} = \dfrac{3V_{1n}}{X_0'}$

and X_0'=capacitive zero sequence shunt reactance of the system

The value of d_0 is always given in per cent or per unit.

Since an unbalance factor is a function of only geometry, it can be calculated using the potential coefficient method [2]. With this method, the individual coefficients are determined and assembled into a j x k matrix.

$$P_{jj} = 2\ln\frac{D_{jj}}{r_j} \tag{2.10}$$

$$P_{jk}=2\ln\frac{D_{jk}}{d_{jk}} \tag{2.11}$$

where: D_{jj}=the distance between the center of conductor j and the center of its image.

D_{jk}=the distance between the center of conductor j and the center of the image of conductor k.

r_j=the radius of conductor j.

d_{jk}=the distance between the centers of conductors j and k.

An image conductor is an imaginary conductor with negative charge that lies below the earth's surface (see Figure 2.1).

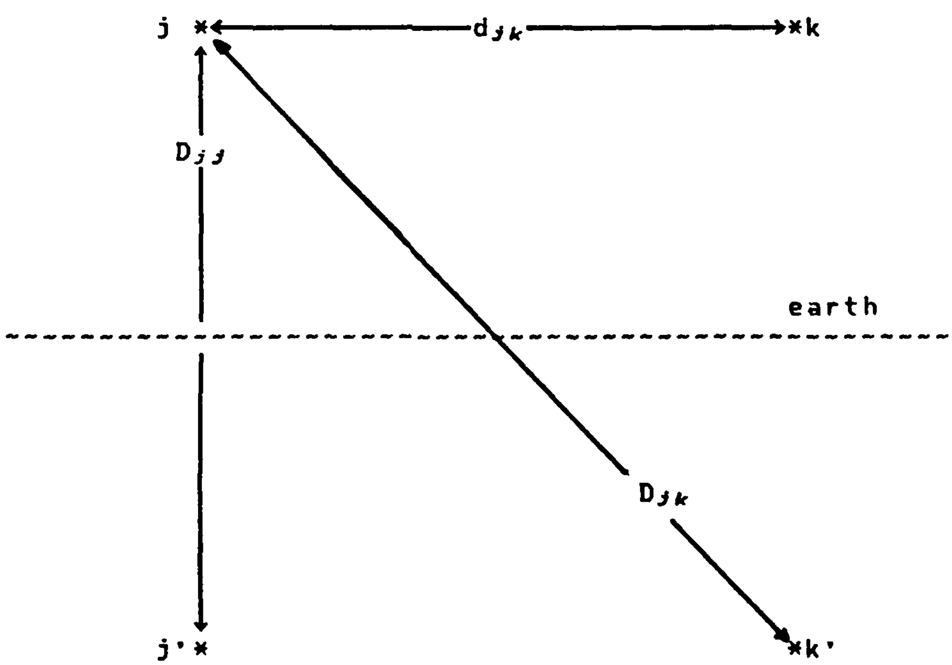


Figure 2.1 Two Conductors With Images

This concept was developed to help derive equations (2.10) and (2.11). Certain assumptions have been made in order to develop equations (2.10) and (2.11) [2].

1. Charges are concentrated at the center of the conductor.
2. The earth is an equipotential surface.
3. Charges assigned to conductor images are equal and opposite to those of actual conductors.

It would not seem appropriate to assume a charge concentrated at the center of the conductor due to skin effects [6]. However, the diameter of the conductors is usually several orders of magnitude smaller than the spacing between the conductors. Thus, the size ratio allows a conductor to be modeled as a line in space. With the charge concentrated on this line the assumption proves its merit. To prove that the earth is an equipotential surface, the same logic can be applied.

Once the potential coefficients are calculated for all j and k, the unbalances can be found. The general solution is [2]:

$$d_0 = \frac{-A+B-C}{A+2B+4C} \tag{2.12}$$

The values of A, B, and C depend upon the existence of ground wires and also upon the conductor configuration.

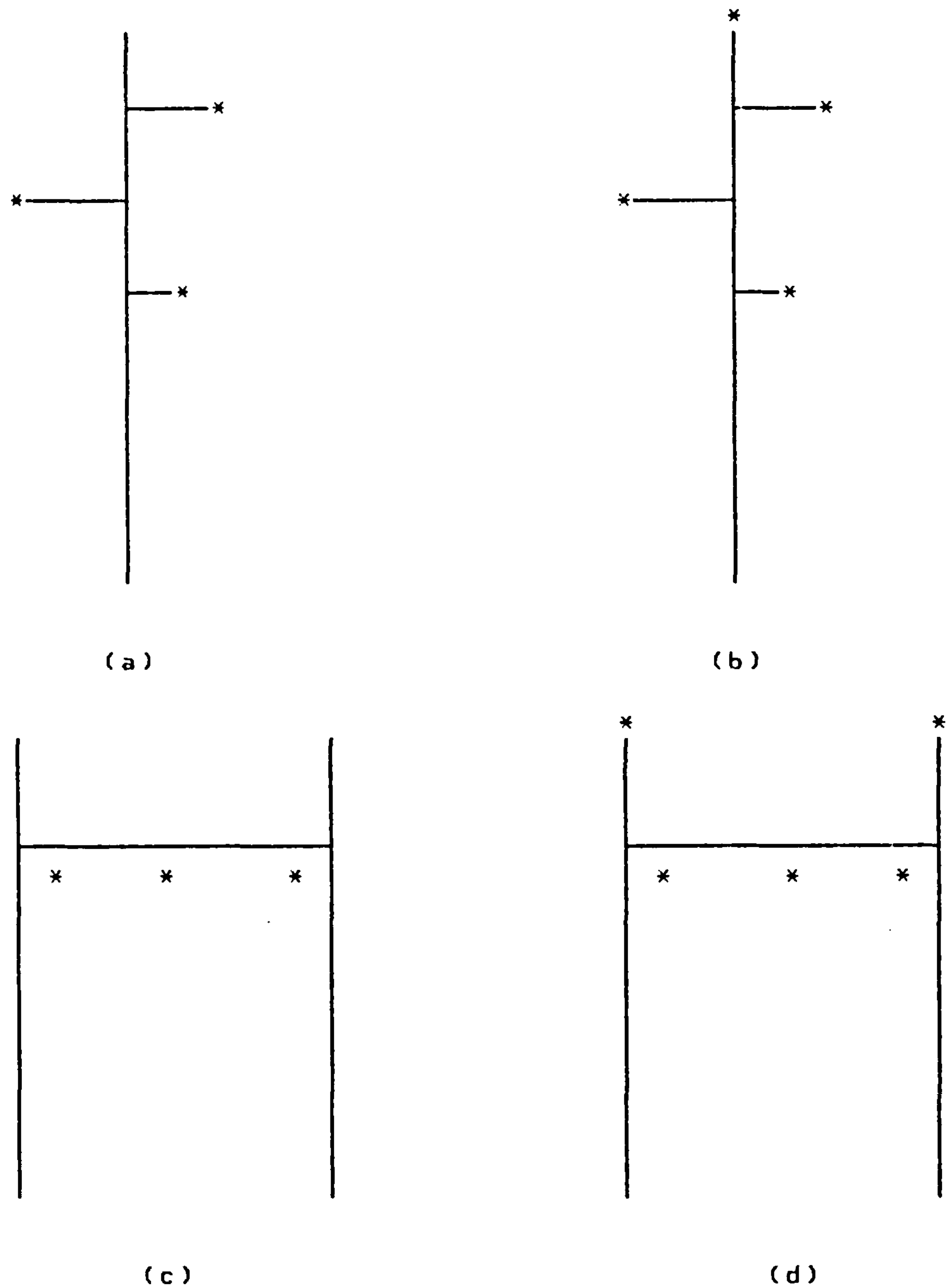


Figure 2.2 Common Circuit Configurations

Figure 2.2 shows several commonly used configurations. For specific values of A, B, and C, the reader is referred to the appendix of "Electrostatic Unbalance to Ground of Twin Conductor Lines" [2].

An alternative method of calculating d_0 exists in the unbalance current method. This method revolves around the basic equation;

$$d_0 = \frac{I_u}{I_{gf}}$$

which was mentioned earlier in this section. According to Gross and McNutt [2], I_u and I_{gf} are defined as follows:

$$I_u = E_{an}\left[\frac{1}{Z_{ag}} + \frac{a^2}{Z_{bg}} + \frac{a}{Z_{cg}}\right] \qquad (2.13)$$

$$I_{gf} = E_{phase}\left[\frac{1}{Z_{ag}} + \frac{1}{Z_{bg}} + \frac{1}{Z_{cg}}\right] \qquad (2.14)$$

where E_{an} is a phase to neutral voltage

and Z_{ag}, Z_{bg}, Z_{cg} are impedances to ground

The resistive component of a phase to ground impedance is small, therefore, the impedance is assumed to be purely reactive. Using this assumption, d_0 can be rewritten in terms of capacitance [2].

$$d_0 = \frac{C_{ag} + a^2 C_{bg} + a C_{cg}}{C_{ag} + C_{bg} + C_{cg}} \tag{2.15}$$

All capacitances in equation (2.15) are phase to ground and the operator a is the phasor quantity $1\angle 120°$ $(a^2 = \angle 240°)$ These phase to ground capacitances can be found using Maxwell's coefficients of the form:

$$q = cV \tag{2.16}$$

where q, c, and V are matrix quantities and the values of c are Maxwell's coefficients.

2.5 Zero Sequence Unbalance Factor

Up to now only the unbalance factor to ground or the ground displacement has been discussed. Another type of unbalance for a transmission system is the zero sequence unbalance factor. This factor is determined solely by the zero sequence charging current. As before, the charging currents are the result of capacitive unbalances of the system. Gross and Chin [7] derive the zero sequence unbalance as follows:

$$d_0' = \frac{I_{a0}'}{I_{a1}'} \tag{2.17}$$

where: I_{a0}' = zero sequence charging current

I_{a1}' = positive sequence charging current

As shown in equation (2.17), once the positive and zero sequence charging currents are known, the unbalance can be calculated.

Since d_0' can eventually be worked into an equality with potential coefficients, one can conclude it to be a function of system geometry.

2.6 Negative Sequence Unbalance Factor

One remaining unbalance factor for electrostatic cases is the negative sequence factor, d_2. Similarities exist between this and the other two unbalance factors. For example, it can also be calculated using sequence charging currents. As the name implies, negative sequence components are used to determine this unbalance factor. The unbalance factor (d_2) is the ratio of the negative to positive sequence charging currents [7]:

$$d_2=\frac{I_{an}'}{I_{a1}'} \qquad (2.18)$$

where: I_{an}'=negative sequence charging current

I_{a1}'=positive sequence charging current

It is also possible to express d_2 as a ratio of potential coefficients. By doing so d_2 becomes dependent on the geometry of the system because the potential coefficients are functions of geometry. However, this thought is not unique, the previous sections discuss the same relationship to system geometry.

2.7 Transposition

Transposition of a power line involves interchanging the conductors so that each conductor occupies each possible position for an equal amount of length. When a line is transposed, all unbalances are eliminated through symmetry [1]. If a line is not transposed, the sequence currents discussed can, and probably will, develop. Zero sequence currents may cause sensitive ground relays to trip. Negative sequence currents can cause a current unbalance and produce additional heating in machines [1].

It is true that transposing a line eliminates these unbalances. But transposition has two main disadvantages: higher cost, and reduced mechanical electrical strength [5]. What Lawrence and Povejsil [5] suggest is to check each individual case to determine if the unbalances are large enough to warrant transposing the line. Other alternatives do exist since the unbalances are a function of geometry.

2.8 Alternatives to Transposition

By now the statement has been made that unbalances are a function of geometry. Since transposing a line seems to have more disadvantages than advantages for certain cases, an alternative must be discussed. One alternative is the manipulation of the phase arrangements, not transposing, but raising and lowering a conductor along its total length. Another alternative is adding ground wires. For example, when ground wires are added to a circuit the unbalance goes down [1]. Of course the amount of decrease depends directly on the placement of the ground wires, but the basic result is important. Also, the ground displacement can be lessened by raising the center conductor in certain configurations.

When the spacing between the phases is increased the unbalance is decreased, but this has practical limits [1]. For instance, a tower has mechanical and cost limitations that would prohibit separating the conductors enough to completely reduce ground unbalance.

Although these methods are not as effective as a complete transposition, adequate results may be obtained if a small amount of unbalance is acceptable.

2.9 Related Electrostatic Studies

Other areas have been investigated in the field of electrostatic effects on transmission lines. Although not as intimately related as the studies discussed, several other studies shed additional light on the area of electrostatic unbalances of transmission lines.

One such study was done by O.W. Anderson [8] and involved the calculation and plotting of field strengths using an iterative computer programming approach. Another noteworthy work was by T.M. McCauley [9]. This study involved electrostatic effects on objects near extra and ultra high voltage transmission lines. McCauley went on to derive formulae for predicting electrostatic effects based on object size, distance from transmission lines, voltage, etc.

CHAPTER 3

MATHEMATICAL MODEL

3.1 Introduction

A mathematical model is necessary to do further studies in the area of electrostatic unbalances of transmission lines. By applying this model to a variety of situations it will be possible to get descriptive data on the types and strengths of unbalances.

An accurate model must be flexible in its application. For example, a transmission line can be transposed or untransposed, have horizontal or vertical spacing, use ground wires or have no ground wires, or may be a double circuit. With this in mind, it is necessary to derive the model to include all practical combinations for transmission lines. In the case of electrostatic unbalances the configuration only changes some basic starting parameters. After this, all cases of unbalance calculations proceed the same.

Before developing the mathematics one additional introductory note is needed. A great deal of matrix algebra will be used in this thesis. Matrix multiplication, inversion, and reduction are the main operators used here. Instead of actually going through the steps of this algebra, only the results will be given. A program titled POWERMAT [10] was developed at Iowa State University, and will be

used to do all of the matrix algebra involved. A computer with software is not always available and techniques that address this will also be reviewed.

3.2 Capacitance Calculations

This model will calculate the capacitive unbalances using potential coefficients. A capacitance will develop between two wires of different voltage. Of course, the capacitance is determined by the strength of the voltage, the distance separating the wires, and some other parameters. This capacitance can take several forms: capacitance between conductors, called mutual capacitance; capacitance between a conductor and ground, called ground capacitance; and the capacitance the conductor induces on itself, called self capacitance.

Once all capacitances of a system are known, the problem of calculating the unbalances becomes somewhat routine. Finding the capacitance matrix, also known as Maxwell's coefficient matrix, is a matter of knowing the system geometry. First the potential coefficient must be found by using equations (3.1) and (3.2) to build the individual components of the original P matrix [4].

$$p_{ij}=\frac{1}{2\pi\epsilon}\ln\frac{H_i}{r_i},\quad i=j \tag{3.1}$$

and

$$p_{ij}=\frac{1}{2\pi\epsilon}\ln\frac{H_{ij}}{D_{ij}},\quad i\neq j \qquad (3.2)$$

For (3.1) and (3.2)

H_i=distance between conductor i and its image.

H_{ij}=distance between conductor i and conductor j's image

r_i=radius of conductor i

D_{ij}=distance between conductor i and conductor j

$$\epsilon=\frac{1}{36\pi\cdot 10^9}$$

Therefore if the system geometry is known, each potential coefficient of the p matrix can be found by using (3.1) and (3.2). Following this the mutual capacitance can be calculated using other relationships.

3.3 Mutual Capacitance of Three-Phase Lines Without Ground Wires

As mentioned before, mutual capacitance is the one that occurs between conductors. If no ground wires exist in the system then no mutual capacitance exists to ground wires, hence the capacitance matrix is somewhat smaller.

Computation of this capacitance matrix is done by using potential coefficients. In Chapter 2, equations for calculating the potential coefficient matrix are shown. This matrix is the key for compiling Maxwell's coefficient matrix, or the capacitance matrix since potential

coefficients and Maxwell's coefficients have an inverse relationship to each other [4].

$$V=Pq \tag{3.3}$$

$$q=cV \tag{3.4}$$

In equations (3.3) and (3.4) the system voltage is represented by V and the charges in different locations are denoted by q. Since V, q, c, and p are all matrix quantities, matrix algebra is necessary for any manipulations. Rewriting equation (3.3) in terms of V,

$$V=\frac{q}{V}=c^{-1}q \tag{3.5}$$

a form very much like equation (3.1) results. Comparing equation (3.3) to equation (3.5) gives:

$$c^{-1}=p \tag{3.6}$$

thus allowing potential coefficients to be used for computing Maxwell's coefficients.

Writing equation (3.4) in matrix form (for a three phase system) gives the proper sign convention for the c matrix [4].

$$\begin{bmatrix} q_a \\ q_b \\ q_c \end{bmatrix} = \begin{bmatrix} c_{aa} & -c_{ab} & -c_{ac} \\ -c_{ba} & c_{bb} & -c_{bc} \\ -c_{ca} & -c_{cb} & c_{cc} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.7}$$

These individual c's are found by the method outlined in the previous section or by direct inversion of the p matrix with a digital computer. *If the line is transposed*, the capacitances are averages of the capacitance seen by each phase in each transposition [4]. Therefore, the mutual capacitance is the average of three individual capacitances [4]:

$$c_{mo} = \left[\ 1/3\ \right] \left[\ c_{ab} + c_{bc} + c_{ac}\ \right] \quad \text{F/mi} \tag{3.8}$$

The capacitance to ground is found by subtracting mutual capacitance from self capacitance (see Figure 3.1).

$$c_{ng} = -c_{na} - c_{nb} - c_{nc} - \cdots\cdots + c_{nn} \quad \text{F/mi} \tag{3.9}$$

Once the capacitance to ground is known, an average value can be calculated that represents a transposed line [4].

$$c_{go} = \left[\ 1/3\ \right] \left[\ c_{ag} + c_{bg} + c_{cg}\ \right] \quad \text{F/mi} \tag{3.10}$$

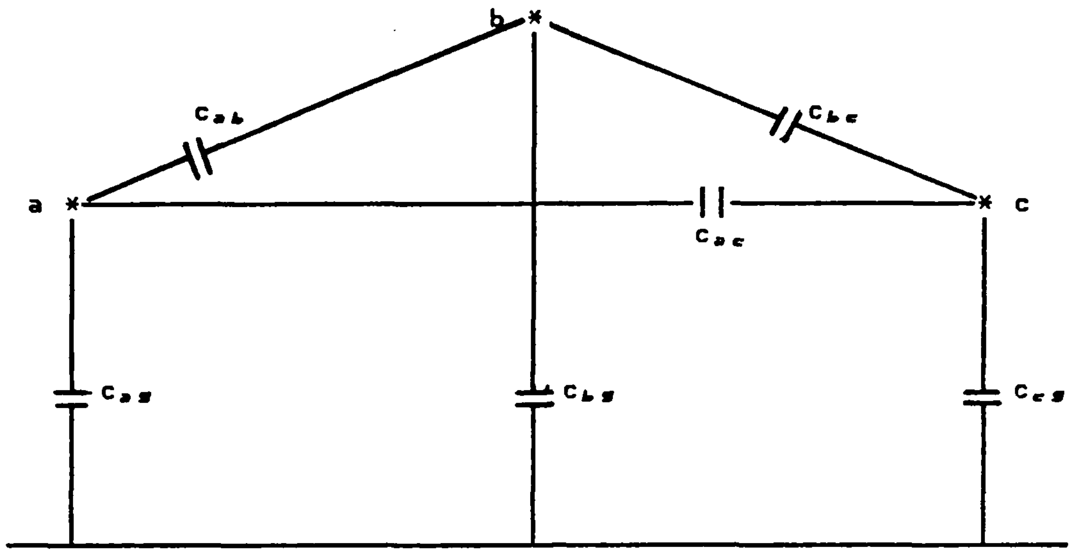


Figure 3.1 Capacitance of Three Phases

Finally, the self capacitance of a transposed line can be derived using the same logic [4].

$$C_{se} = \left[1/3 \right] \cdot \left[C_{aa} + C_{bb} + C_{cc} \right] \quad \text{F/mi} \qquad (3.11)$$

The self, mutual, and ground capacitances will later be used to define the actual unbalance factors. For now, equations (3.8) thru (3.11) show how to calculate average values of capacitance for a transposed line having three phases and no ground wires. Obviously, if the line were not transposed the values would be different; that is a topic left for Section 3.9. The values of capacitance also change

when overhead ground wires are used. This is left for discussion in Section 3.5.

3.4 Sequence Capacitance Without Ground Wires

As in the previous section the case to be dealt with will involve a transposed transmission line. Like all other vector quantities, symmetrical components can be derived from Maxwell's coefficient matrix. Because of the phasor relationship [3]

$$I=j\omega cV \qquad (3.12)$$

several other relationships can be derived. For example, equation (3.12) can be written in one of two coordinate system: the a-b-c or the 0-1-2. Since the sequence components are of interest, equation (3.12) will be rewritten as follows [4]:

$$I_{012}=j\omega c_{012}V_{012} \qquad (3.13)$$

It is possible to convert in and out of symmetrical and phase components using the a operator described in Chapter 2. To change C_{abc} into C_{012} requires nothing but matrix multiplication [4]

$$c_{012}=A^{-1}c_{abc}A=\begin{bmatrix} c_{00} & c_{01} & c_{02} \\ c_{10} & c_{11} & c_{12} \\ c_{20} & c_{21} & c_{22} \end{bmatrix} \tag{3.14}$$

where $A=\begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$

and $A^{-1}= 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}$

If the C_{abc} matrix of equation (3.7) were premultiplied by A^{-1} and postmultiplied by A as in (3.14) the result would be the matrix of equation (3.15) [4].

$$c_{012}=\begin{bmatrix} (c_{s0}-2c_{m0}) & (c_{s2}+c_{m2}) & (c_{s1}+c_{m1}) \\ (c_{s1}+c_{m1}) & (c_{s0}+c_{m0}) & (c_{s2}-2c_{m2}) \\ (c_{s2}+c_{m2}) & (c_{s1}-c_{m1}) & (c_{s0}+c_{m0}) \end{bmatrix} \tag{3.15}$$

where $c_{s1}=\begin{bmatrix} 1/3 \end{bmatrix}\begin{bmatrix} c_{aa}+ac_{bb}+a^2c_{cc} \end{bmatrix}$

$c_{s2}=\begin{bmatrix} 1/3 \end{bmatrix}\begin{bmatrix} c_{aa}+a^2c_{bb}+ac_{cc} \end{bmatrix}$

$c_{m1}=\begin{bmatrix} 1/3 \end{bmatrix}\begin{bmatrix} c_{bc}+ac_{ac}+a^2c_{ab} \end{bmatrix}$

$c_{m2}=\begin{bmatrix} 1/3 \end{bmatrix}\begin{bmatrix} c_{bc}+a^2c_{ac}+ac_{ab} \end{bmatrix}$

Note that the matrix of equation (3.15) is not transposed. If a typical phase component matrix (eg C_{abc}) is manipulated as in equation (3.14), the result will be matrix equation (3.15). When the line is known to be transposed, mutual coupling between the networks is eliminated [4]. Mathematically this elimination occurs by the multiplication of $(1+a+a^2)$ by each capacitance term of C_{s1}, C_{s2}, C_{m1}, and C_{m2} [4]. The multiplier $(1+a+a^2)$ comes from the phasor shift that occurs as transposition is modeled mathematically. However, when anything is multiplied by $(1+a+a^2)$ the vector sum is zero. Thus, all off diagonal terms are eliminated to produce [4]

$$c_{012}=\begin{bmatrix} (c_{so}-2c_{mo}) & 0 & 0 \\ 0 & (c_{so}+c_{mo}) & 0 \\ 0 & 0 & (c_{so}+c_{mo}) \end{bmatrix} \qquad (3.16)$$

Notice that $C_{11}=C_{22}=C_{s0}+C_{m0}$. This is a characteristic of a transposed line with no ground wires. Another characteristic is the zero sequence, C_{00}, is less than the positive and negative sequence.

3.5 Mutual Capacitance of Three Phase Line With Ground Wires

After demonstrating various capacitances of a three phase system without ground wires it is necessary to recalculate these components with the addition of ground wires. Adding ground wires complicates the matrix algebra

involved, but it more realistically reflects a typical high voltage transmission line.

In keeping with the last section, a transposed line will be considered first. For the case of one ground wire the initial problem of the last section is complicated by expanding the voltage, charge, and potential coefficient matrix. Starting with equation (3.3) as a matrix relationship yields [4]

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ -- \\ 0 \end{bmatrix} = \left[\begin{array}{ccc|c} p_{aa} & p_{ab} & p_{ac} & p_{an} \\ p_{ba} & p_{bb} & p_{bc} & p_{bn} \\ p_{ca} & p_{cb} & p_{cc} & p_{cn} \\ \hline p_{na} & p_{nb} & p_{nc} & p_{nn} \end{array}\right] \begin{bmatrix} q_a \\ q_b \\ q_c \\ -- \\ q_n \end{bmatrix} \qquad (3.17)$$

In equation (3.17) the last row of the voltage matrix is zero. This is in keeping with the last row representing the voltage of the ground wire (the n^{th} row).

As before, this potential matrix must be inverted to yield Maxwell's coefficient matrix C. Once C is found, the self, mutual, and ground capacitances can be found and used to calculate any unbalance factors.

As evidenced in equation (3.17), the addition of one ground wire adds one row to each matrix and one column to the charge matrix. The addition of two ground wires to the original three phase system adds two rows to all matrices and two columns to the charge matrix q [4].

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ -- \\ 0 \\ 0 \end{bmatrix} = \left[\begin{array}{ccc|cc} p_{aa} & p_{ab} & p_{ac} & p_{am} & p_{an} \\ p_{ba} & p_{bb} & p_{bc} & p_{bm} & p_{bn} \\ p_{ca} & p_{cb} & p_{cc} & p_{cm} & p_{cn} \\ \hline p_{ma} & p_{mb} & p_{mc} & p_{mm} & p_{nn} \\ p_{na} & p_{nb} & p_{nc} & p_{nn} & p_{mn} \end{array}\right] \begin{bmatrix} q_a \\ q_b \\ q_c \\ -- \\ q_n \\ q_m \end{bmatrix} \tag{3.18}$$

In equation (3.18) the ground wires are labeled m and n, and both ground wires are represented with a zero potential. Notice in equations (3.17) and (3.18) the dashed lines inside the matrix. These lines serve as a partition to divide for calculating C_{abc}. By partitioning the matrix as shown, a Kron reduction can be performed [10]. This reduction yields a simplified matrix that includes a correction for ground wires [4]. Rewriting equation (3.18) as

$$\begin{bmatrix} V_{abc} \\ ---- \\ 0 \end{bmatrix} = \left[\begin{array}{c|c} P_1 & P_2 \\ \hline P_3 & P_4 \end{array}\right] \begin{bmatrix} q_{abc} \\ ---- \\ q_{mn} \end{bmatrix} \tag{3.19}$$

shows the individual components of p involved in the reduction formula [4]. Now a new P may be calculated using equation (3.20)

$$P_{abc} = P_1 - P_2 P_4^{-1} P_3 \tag{3.20}$$

as the method of reduction. The matrix P_{abc} of equation (3.20) is identical in size to the C matrix of equation (3.7). Therefore it can be inverted to yield a Maxwell's coefficient matrix representing a three phase system corrected for "n" ground wires.

If the sequence capacitance is needed the matrix C_{abc} can be treated as in the past (see equation 3.14) to yield the desired form.

3.6 Capacitance of Single Circuit Vertical Configuration

How to calculate the various forms of capacitance for a circuit with and without ground wires has been shown. So far no mention has been made of what position or configuration the actual conductor occupies. In the case of a vertical configuration (see Figure 2.2) the procedures covered so far will work. Of course, the accuracy depends on the number of decimal places carried and the use of formulas corresponding to the presence or absence of ground wires. The importance of the potential coefficients are what should be emphasized.

Since the potential coefficients are based on raw geometry, all subsequent calculations of this chapter adopt the same dependence. Therefore, it is of little consequence if the circuit is vertical , providing the p matrix is calculated with that configuration in mind.

3.7 Capacitance of a Horizontal Circuit

Though critically important for computing an accurate unbalance factor, the configuration is only used to calculate the potential coefficients. Naturally, the p matrix effects capacitance, and capacitance effects unbalance. However, once the p matrix is calculated based on the height above ground, radius, and position of the conductors, the circuit configuration can be ignored for calculating purposes.

3.8 Double Circuit Capacitance

A double circuit is, much as the name implies, two parallel and independent circuits. With a double circuit the potential coefficient matrix becomes at least twice as big because of the increased number of charges. A three-phase single circuit without ground wires produces a 3X3 p matrix. A three-phase double circuit without ground wires yields a 6X6 p matrix; this is a minimum size.

The resulting 6X6, or larger, p matrix complicates the matrix manipulation but not the theory. The capacitances are still calculated via the p matrix and this potential matrix is still calculated by the methods covered. It is the size of the potential matrix that poses the difficulty. A typical V=gV expression for a double circuit having no ground wires is written:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ -- \\ V_{a'} \\ V_{b'} \\ V_{c'} \end{bmatrix} = \left[\begin{array}{ccc|ccc} p_{aa} & p_{ab} & p_{ac} & p_{aa'} & p_{ab'} & p_{ac'} \\ p_{ba} & p_{bb} & p_{bc} & p_{ba'} & p_{bb'} & p_{bc'} \\ p_{ca} & p_{cb} & p_{cc} & p_{ca'} & p_{cb'} & p_{cc'} \\ \hline p_{a'a} & p_{a'b} & p_{a'c} & p_{a'a'} & p_{a'b'} & p_{a'c'} \\ p_{b'a} & p_{b'b} & p_{b'c} & p_{b'a'} & p_{b'b'} & p_{b'c'} \\ p_{c'a} & p_{c'b} & p_{c'c} & p_{c'a'} & p_{c'b'} & p_{c'c'} \end{array}\right] \begin{bmatrix} q_a \\ q_b \\ q_c \\ -- \\ q_{a'} \\ q_{b'} \\ q_{c'} \end{bmatrix} \tag{3.21}$$

with abc and a'b'c' being the two circuits [4].

Notice the dotted lines dividing equation (3.21). These lines are the same as the ones used to Kron reduce previous examples. A reduction is performed along the dotted lines to yield a 3 X 3 p matrix.

To obtain a more workable matrix, equation (3.21) must be rewritten as follows [4]:

$$\begin{bmatrix} V_{abc} \\ V_{a'b'c'} \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix} \begin{bmatrix} q_{abc} \\ q_{a'b'c'} \end{bmatrix} \tag{3.22}$$

In this form, C is found by direct inversion of p in its four parts [4].

$$C = P^{-1} = \begin{bmatrix} (P_{11}^{-1}+FE^{-1}F^{t}) & (-FE^{-1}) \\ (-FE^{-1})^{t} & (E^{-1}) \end{bmatrix} \tag{3.23}$$

where $E = P_{22}-P_{21}P_{11}^{-1}P_{12}$
$F = P_{11}^{-1}P_{12}$

The C matrix of equation (3.23) is still a 6 X 6 matrix. If the matrix is broken into four parts where,

$$\begin{aligned} C_1 &= P_{11}^{-1} + FE^{-1}F^t \\ C_2 &= (-FE^{-1}) \\ C_3 &= (-FE^{-1})^t \\ C_4 &= (E^{-1}) \end{aligned} \tag{3.24}$$

then an equivalent matrix C_{eq} can be calculated as

$$C_{eq} = C_1 + C_2 + C_3 + C_4 \tag{3.25}$$

which is a 3x3 matrix [4].

This C_{eq} represents the capacitance of the parallel or double circuit. If necessary the ground, mutual, or self impedance can be calculated for C_{eq} using equations (3.8), (3.10), and (3.11). Also note that a sequence matrix C_{012} can be obtained by the method of (3.14) [4].

$$C_{012} = A^{-1} C_{eq} A \tag{3.26}$$

If ground wires are added, the p matrix is further complicated. For instance, two ground wires add two rows and two columns to the potential matrix. Like before, the matrix must be Kron reduced to eliminate the excess rows and columns. Only then can the techniques given equation in (3.21) through (3.26) be used.

3.9 Electrostatic Unbalances of Untransposed Lines

Transposing a transmission line was a technique used heavily in the past to eliminate unbalances. Lawrence [6] and others argue this method is not always necessary if some unbalance is acceptable.

Calculating the unbalance factor is the focal point of this chapter. To find the displacement or zero sequence unbalance it must first be decided if the system is grounded. If the system is not grounded, two assumptions can be made [4]:

1. The neutral voltage will be nonzero $V_n \neq 0$
2. The neutral current will be zero $I_{a0} = 0$

Anderson [4] defines the neutral displacement as:

$$d_0 = \frac{V_{a0}}{V_{a1}} = -\frac{C_{01}}{C_{00}} \qquad (3.27)$$

Using equation (3.15) and (3.11), d_0 can be rewritten [4]:

$$d_0 = \frac{-(C_{s2} + C_{m2})}{C_{go}} \qquad (3.28)$$

If d_0 is wanted in terms of capacitances to ground it can be written as follows [4]:

$$d_0=\frac{C_{ag}+a^2C_{bg}+aC_{cg}}{C_{ag}+C_{bg}+C_{cg}}=\frac{C_{ag}+a^2C_{bg}+aC_{cg}}{3C_{go}} \tag{3.29}$$

Another possibility exists: the case of the neutral being solidly grounded. For this system, the neutral voltage will be zero, $V_n=0$, because of the return path to ground. Anderson [4] describes the solidly grounded displacement again with capacitance.

$$d_0=\frac{I_{a0}}{I_{a1}}=\frac{C_{01}}{C_{11}} \tag{3.30}$$

Expanding equation (3.30), the same as for equation (3.27) yields

$$d_0=\frac{C_{ag}+a^2C_{bg}+aC_{cg}}{(C_{ag}+C_{bg}+C_{cg})\ +\ 3(C_{ab}+C_{bc}+C_{ca})} \tag{3.31}$$

knowing that $C_{ag}+C_{bg}+C_{cg}=3C_{g0}$ and $C_{ab}+C_{bc}+C_{ca}=3C_{m0}$, equation (3.31) is rewritten in the form

$$d_0=\frac{C_{ag}+a^2C_{bg}+aC_{cg}}{3(C_{go}+3C_{mo})} \tag{3.32}$$

to make use of the previously derived mutual and ground capacitance terms. Usually the capacitance between the conductors is much smaller than the capacitance to ground

[4]. With this in mind, the conductor or mutual capacitance is neglected to produce

$$d_0=\frac{C_{ag}+a^2C_{bg}+aC_{cg}}{3C_{go}} \tag{3.33}$$

which is the same as the ungrounded case, equation (3.29) [4].

For a complete understanding of electrostatic unbalances, the negative sequence unbalance must be discussed. Anderson [4] defines this negative sequence unbalance as a ratio of sequence currents.

$$d_2=\frac{I_{a2}}{I_{a1}}=-\frac{C_{21}}{C_{11}} \tag{3.34}$$

It is obvious that the capacitances of equation (3.34) can be manipulated into a more common form using prior relationships.

$$d_2=\frac{C_{m1}-C_{s1}}{C_{so}+C_{mo}} \tag{3.35}$$

3.10 Unbalances of a System

Using the relationship derived in this chapter, it will be possible to calculate all electrostatic unbalances for a three phase transmission line. As demonstrated, single circuits with horizontal and vertical spacing, double circuits, and circuits with or without ground wires can be solved to find unbalances.

What is necessary now is to expand past studies and calculate various unbalances for a large number of different situations. Once done, new and useful conclusions may be drawn.

CHAPTER 4

APPLICATION OF MODEL

4.1 Introduction

The actual application of the model is the topic of this chapter. In the last chapter, two entirely different methods were used to calculate electrostatic unbalances. One method is designed for a calculator while the other utilizes a digital computer. As previously mentioned, a computer will be used for this project.

The model described in Chapter 3 will be applied to a variety of circuits. However, the circuit will be 100 miles long and have bundled conductors. Because of the nature of electrostatic unbalances, their magnitude is independent of system voltage or current. Therefore, neither a voltage or current reference will be given. The only variables of this work will be conductor size and tower geometry. In all, 27 different wire sizes will be studied on 26 entirely different circuit arrangements.

4.2 Bundled Conductors

The use of bundled conductors makes the system more realistic but multiplies the difficulty of the matrix algebra. A two wire bundle was used here. Each phase is made up of two conductors on 18" centers and installed parallel to the ground. The result of using bundled

conductors is a more complex potential matrix. For example, if each phase of a three phase system were only single a conductor, the applicatio of equation (3.1) and (3.2) would yield a 3x3 P matrix.

$$P_{abc} = \begin{bmatrix} P_{aa} & P_{ab} & P_{ac} \\ P_{ba} & P_{bb} & P_{bc} \\ P_{ca} & P_{cb} & P_{cc} \end{bmatrix} \quad (4.1)$$

If this same three phase system used bundled conductors (two per phase) the resultant potential matrix would be significantly larger.

$$P_{abcrst} = \begin{bmatrix} P_{aa} & P_{ab} & P_{ac} & P_{ar} & P_{as} & P_{at} \\ P_{ba} & P_{bb} & P_{bc} & P_{br} & P_{bs} & P_{bt} \\ P_{ca} & P_{cb} & P_{cc} & P_{cr} & P_{cs} & P_{ct} \\ P_{ra} & P_{rb} & P_{rc} & P_{rr} & P_{rs} & P_{rt} \\ P_{sa} & P_{sb} & P_{sc} & P_{sr} & P_{ss} & P_{st} \\ P_{ta} & P_{tb} & P_{tc} & P_{tr} & P_{ts} & P_{tt} \end{bmatrix} \quad (4.2)$$

It should be easily recognized that the presence of one additional wire per phase quadruples the size of the potential matrix. If a three wire bundle were used, a 9x9 matrix would result. Equation (4.2) is the building block for all subsequent manipulations, therefore, a smaller size would be useful. An equivalent form of equation (4.2) is found by a technique used by Anderson [4] which reduces the potential matrix to a 3x3 as in equation (4.1).

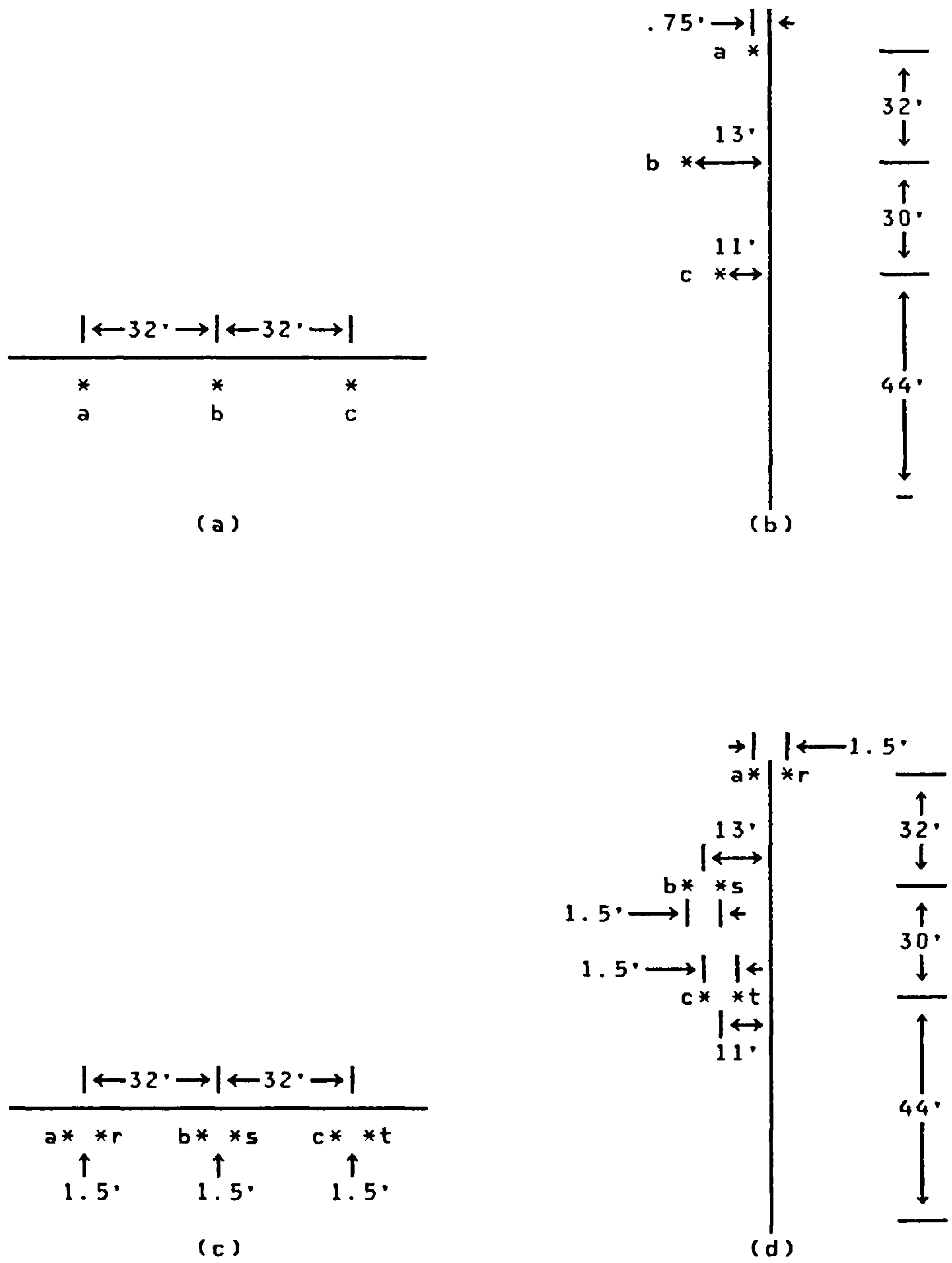


Figure 4.1 Single Circuit Configurations: (a) Horizontal Nonbundled, (b) Vertical Nonbundled, (c) Horizontal Bundled, (d) Vertical Bundled

This reduction is equivalent to reducing Figure 4.1(b) to Figure 4.1(a). Naturally a program was used to reduce equation (4.2), details are shown below. The basic steps of this reduction are as follows:

1.) Partition P_{abcrst} into four 3x3 sections

$$P_{abcrst}=\left[\begin{array}{c|c} p_{11} & p_{12} \\ \hline p_{21} & p_{22} \end{array}\right] \qquad (4.3)$$

2.) Using the four sections a reduced 3x3 matrix, P_{new}, is found [4].

$$P_{new}=P_{11}\Big[(P_{12}-P_{11})([P_{11}-P_{12}] - [P_{21}-P_{11}])^{-1}(P_{21}-P_{11}) \Big] \qquad (4.4)$$

This P_{new} is a mathematical reduction of a more complex system. Instead of manipulating a larger matrix that is the exact representation of a bundled conductor system, a smaller equivalent will be used. Table 4.1 and 4.2 list the dimensions of the single bundled circuits (Figure 4.1(a) and 4.1(b)) used in the research. The addition of ground wires as well as the use of double circuits also complicates the potential matrix. That matter will be attended to in later sections.

Table 4.1 Single Horizontal Circuit Dimensions

HORIZONTAL CIRCUIT			
D_{ab}	32.0000'	H_{aa}	200.0000'
D_{ac}	64.0000'	H_{ab}	202.5438'
D_{ar}	1.5000'	H_{ac}	209.9905'
D_{as}	33.5000'	H_{ar}	200.0056'
D_{at}	53.5000'	H_{as}	202.7862'
D_{ba}	32.0000'	H_{at}	210.4525'
D_{br}	32.0000'	H_{bb}	200.0000'
D_{bt}	30.5000'	H_{bc}	202.5438'
D_{bs}	1.5000'	H_{br}	202.3123'
D_{ca}	33.5000'	H_{bs}	200.0056'
D_{cb}	64.0000'	H_{bt}	202.7862'
D_{cr}	32.5000'	H_{cc}	200.0000'
D_{cr}	62.5000'	H_{cr}	202.7862'
D_{cs}	30.5000'	H_{cs}	202.3123'
D_{ct}	1.5000'	H_{ct}	200.0056'

Table 4.2 Single Vertical Circuit Dimensions

VERTICAL CIRCUIT			
D_{ab}	34.5398'	H_{aa}	212.0000'
D_{ac}	62.0323'	H_{ab}	180.4688'
D_{ar}	1.5000'	H_{ac}	150.0133'
D_{as}	34.0037'	H_{ar}	212.0053'
D_{at}	62.0020'	H_{as}	180.3670'
D_{ba}	34.5398'	H_{at}	150.0008'
D_{bc}	31.9531'	H_{bb}	148.0000'
D_{br}	35.1319'	H_{bc}	118.5116'
D_{bs}	1.5000'	H_{bs}	180.5831'
D_{bt}	32.5000'	H_{bs}	148.0076'
D_{ca}	62.0323'	H_{bt}	118.6602'
D_{cb}	31.9531'	H_{cc}	88.0000'
D_{cr}	62.0987'	H_{cr}	150.0408'
D_{rs}	31.4682'	H_{cs}	118.3818'
D_{ct}	1.5000'	H_{ct}	88.0128'

4.3 Single Horizontal Circuit With No OHGW

Of the 27 wire sizes listed on Table 4.3, 500 MCM will be frequently referred to for comparison. The choice of 500 MCM is completely arbitrary, as any other size could be used. Using 500 MCM in the single horizontal circuit (Figure 4.1(b)), the calculation of the potential matrix yields:

$$P_{abcrst}=\begin{bmatrix} 95.7965 & 20.6101 & 13.2713 & 54.6508 & 20.1118 & 13.0371 \\ 20.6101 & 95.7965 & 20.6101 & 21.1336 & 54.6508 & 20.1118 \\ 13.2713 & 20.6101 & 95.7965 & 13.1463 & 21.1336 & 54.6508 \\ 54.6508 & 21.1336 & 13.1463 & 95.7965 & 20.6101 & 13.2713 \\ 20.1118 & 54.6508 & 21.1336 & 20.6101 & 95.7965 & 20.6101 \\ 13.0371 & 20.1118 & 54.6508 & 13.2713 & 20.6101 & 95.7965 \end{bmatrix} \tag{4.5}$$

From this point forward the unbalance algorithm is somewhat systematic. The system is reduced, inverted, multiplied by 100, then converted to symmetrical components. Once the system is in symmetrical component form, the unbalances are found as a ratio of the matrix elements. Equation (4.5) can be reduced by the method outlined; doing so results in the equivalent 3x3 matrix of equation (4.6).

$$P_{abc}=\begin{bmatrix} 75.2204 & 20.6160 & 13.1847 \\ 20.6160 & 75.2173 & 20.6160 \\ 13.1847 & 20.6160 & 75.2204 \end{bmatrix} \tag{4.6}$$

Table 4.3 Twenty-Seven Conductor Sizes

Circular Mils	Strand		Radius (inches)	Radius (feet)
	Al.	St.		
1 590 000	54	19	.7728	.0644
1 510 000	54	19	.7536	.0628
1 431 000	54	19	.7320	.0610
1 351 000	54	19	.7116	.0593
1 272 000	54	19	.6912	.0576
1 192 000	54	19	.6696	.0558
1 133 000	54	19	.6468	.0539
1 033 000	54	7	.6228	.0519
954 000	54	7	.5976	.0498
900 000	54	7	.5808	.0484
874 000	54	7	.5736	.0478
795 000	54	7	.5460	.0455
795 000	26	7	.5544	.0462
795 000	30	19	.5700	.0475
715 000	54	7	.5184	.0432
715 000	26	7	.5256	.0438
715 000	30	19	.5400	.0450
666 600	54	7	.5004	.0417
636 000	54	7	.4884	.0407
636 000	26	7	.4956	.0413
636 000	30	19	.5100	.0425
605 000	54	7	.4764	.0397
605 000	26	7	.4836	.0403
556 000	26	7	.4632	.0386
556 000	30	7	.4764	.0397
500 000	30	7	.4524	.0377
477 000	26	7	.4296	.0358

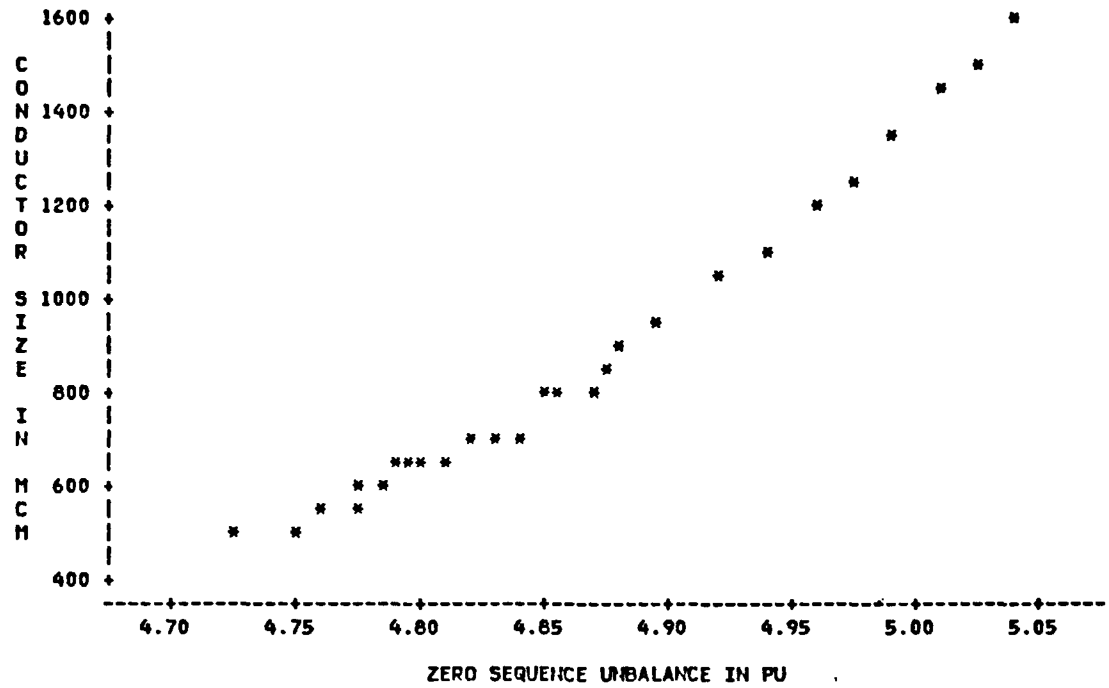
Inverting (4.6) yields a capacitance matrix, C_{abc}, in phase components. Further use of the computer to change the phase components into symmetrical components, C_{012}, is required for final analysis (see equation 3.26).

It should be noted that at any time the 100 miles of line can be considered by multiplying each element of P, C_{abc}, or C_{012} by 100. However, when the unbalances are calculated, the 100 will be nullified as it appears in both numerator and denominator of the unbalance fraction. The sequence capacitance matrix for 500 MCM of the circuit is shown in equation (4.7).

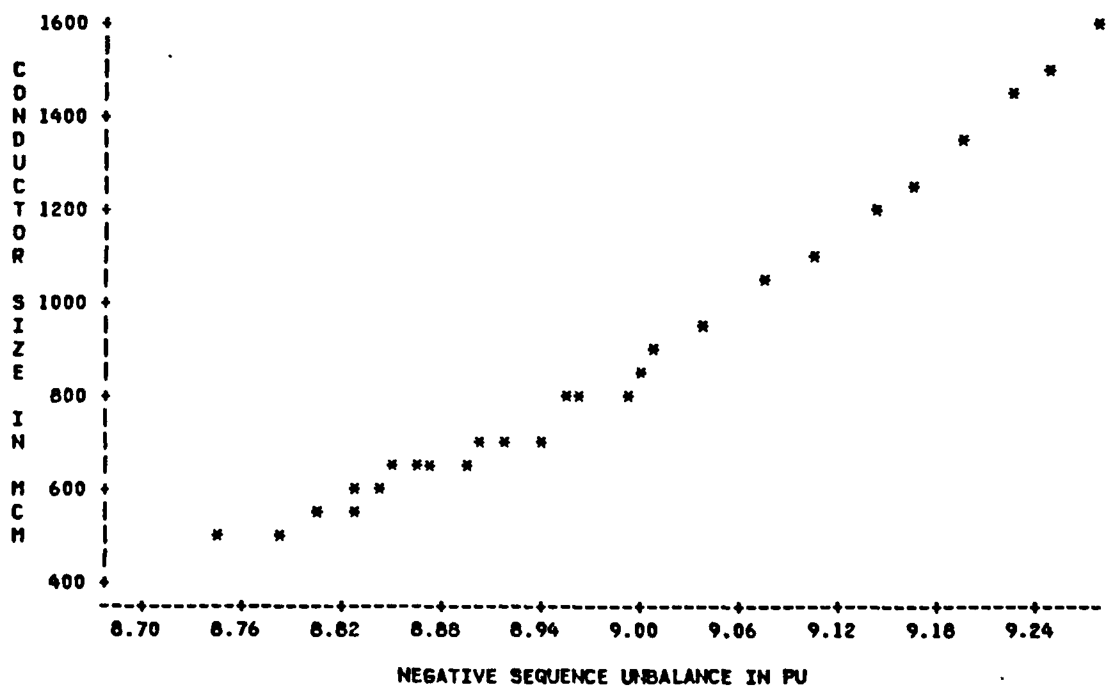
$$C_{012}=\begin{bmatrix} .8988+J0.0 & .0213+J.0370 & .0213+J.0370 \\ .0213-J.0370 & 1.7672+J0.0 & -.0776-J.1345 \\ .0213+J.0370 & -.0776+J.1345 & 1.7672-J0.0 \end{bmatrix} \tag{4.7}$$

Zero sequence unbalance is found as the negative of the ratio of c_{01} to c_{00}. If the system has one or more overhead ground wires (OHGW), then replace c_{00} with $-c_{11}$.

$$d_0=-\frac{C_{01}}{C_{00}} = 4.7502E\text{-}02\angle\underline{-120.00^\circ}\ \% \tag{4.8}$$



(a)



(b)

Figure 4.2 Wire Size In MCM Versus Unbalance for Single Horizontal Circuit With No OHGW (a) Zero Sequence, (b) Negative Sequence

The negative sequence unbalance is found in a similar manner using

$$d_2 = \frac{C_{21}}{C_{11}} = 8.7860E\text{-}02 \angle \underline{-60.00°}\ \% \qquad (4.9)$$

Both equation (4.8) and (4.9) are per unit quantities with attached angles. Figure 4.2(a) and (b) show the variation of the unbalance magnitude for all 27 wire sizes for the zero and negative sequence. In both cases the unbalance has a clear relationship to the size of the wire. Examining the plots reveal that the zero and negative sequence electrostatic unbalance increases with increased wire size. Also notice for this particular circuit arrangement the negative sequence unbalance is the larger of the two. For a final comparison of the unbalance data of this circuit Table A.1 is included in the appendix and lists the magnitudes and angles of each unbalance.

4.4 Single Vertical Circuit With No OHGW

The process of finding the unbalance of a vertical circuit is identical to that of the horizontal circuit. Only the values affected by geometry, that is, the tower distances will change. Ultimately the P matrix will change as a result of different geometry.

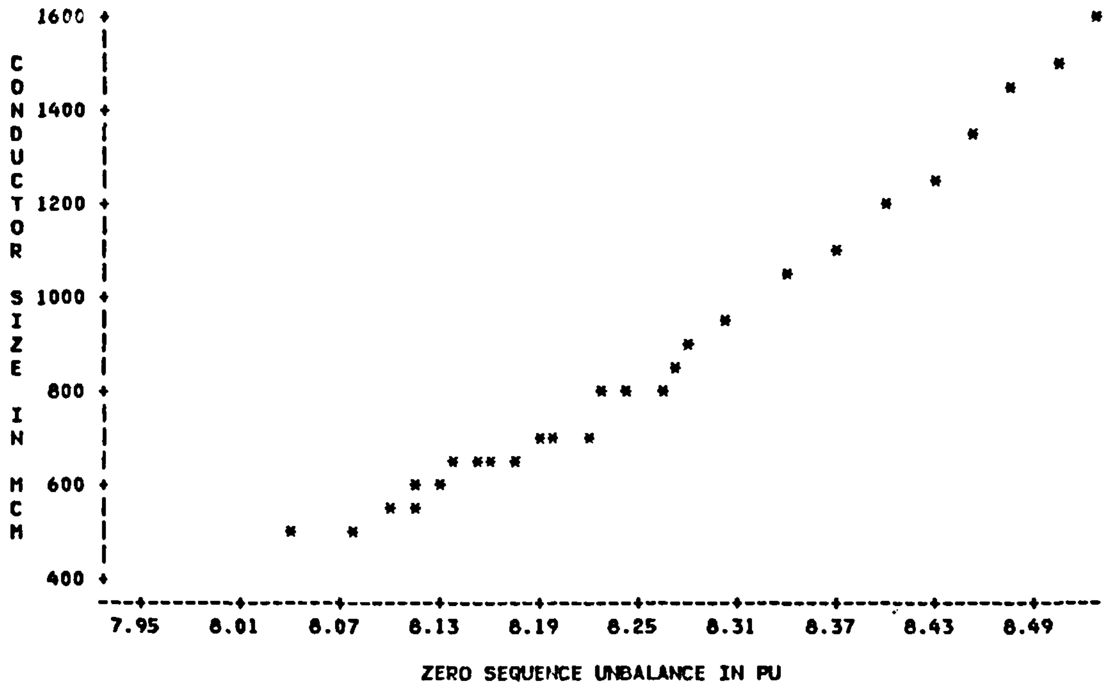
Again using 500 MCM, the potential matrix for a single vertical circuit is calculated; the result is shown below.

$$P_{abcrst}=\begin{bmatrix} 96.4428 & 18.4677 & 9.8636 & 55.3019 & 18.6368 & 9.8680 \\ 18.4677 & 96.4428 & 14.6401 & 18.0272 & 51.2879 & 14.7756 \\ 9.8636 & 14.6401 & 96.4428 & 9.8537 & 14.7985 & 45.4818 \\ & & & & & \\ 55.3019 & 18.0272 & 9.8537 & 96.4428 & 18.4677 & 9.8636 \\ 18.6368 & 51.2879 & 14.7985 & 18.4677 & 96.4428 & 14.6401 \\ 9.8680 & 14.7756 & 45.5818 & 9.8636 & 14.6401 & 96.4428 \end{bmatrix} \tag{4.10}$$

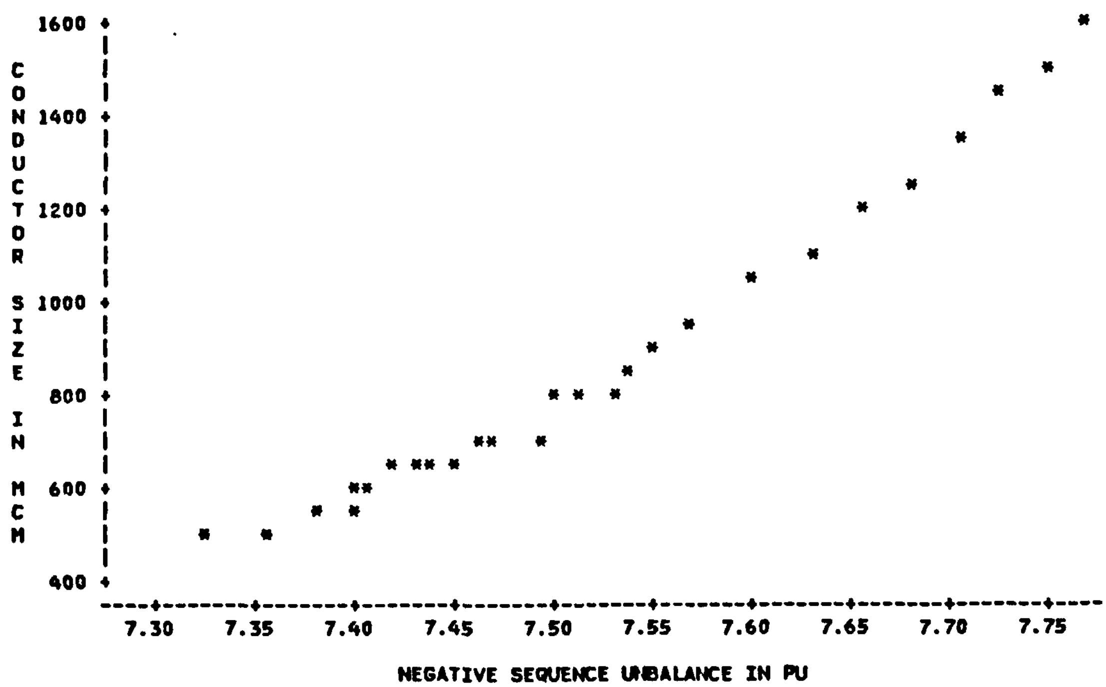
The matrix above is a 6x6 and of a bulky form. The reduction technique discussed earlier can be applied to equation (4.10) with the result being the more compact 3x3 matrix shown in equation (4.11).

$$P_{abc}=\begin{bmatrix} 75.8712 & 18.3998 & 9.8622 \\ 18.3998 & 71.8642 & 14.7135 \\ 9.8622 & 14.7135 & 66.0535 \end{bmatrix} \tag{4.11}$$

When P_{abc} is inverted and multiplied by 100 it becomes the phase capacitance representation of the system. Using symmetrical component analysis techniques the sequence capacitance can be readily determined. It is this matrix that is the desired final form as all unbalance calculations are done with its elements.



(a)



(b)

Figure 4.3 Wire Size In MCM Versus Unbalance for Single Vertical Circuit for (a) Zero Sequence, (b) Negative Sequence.

$$C_{012}=\begin{bmatrix} 1.0055 & -.0314 & -.0314 \\ +J0.0 & +J.0745 & \_J.0745 \\ & & \\ -.0314 & 1.7636 & -.0872 \\ -J.0745 & -J0.0 & -J.0953 \\ & & \\ -.0314 & -.0872 & 1.7636 \\ +J.0745 & +J.0953 & +J0.0 \end{bmatrix} \quad (4.12)$$

Finally, the matrix of equation (4.12) is used to calculate the actual electrostatic unbalance for a single vertical circuit. Using the relationship of equation (4.8) and (4.9), the per unit unbalance for a given wire size can be found. When all 27 conductor sizes are similarly analyzed enough data exists to plot conductor size in MCM versus unbalance. These plots appear on Figure 4.3(a) and (b). Notice again the change in unbalance over the range of conductor sizes. As in the case of the horizontal single arrangement, the unbalance goes up when the conductor size goes up. This observation applies to both the zero sequence and the negative sequence. Unlike its horizontal counterpart, the zero sequence unbalance factor is the larger of the two numbers.

4.5 Double Horizontal Circuit Without OHGW

Often times double circuits are used. As a result, they will be studied as part of this project. The double circuit is shown in Figures 4.4(a) through (f). Just as in the bundled conductor case, the double circuit complicates the potential matrix. Notice the circuit composition

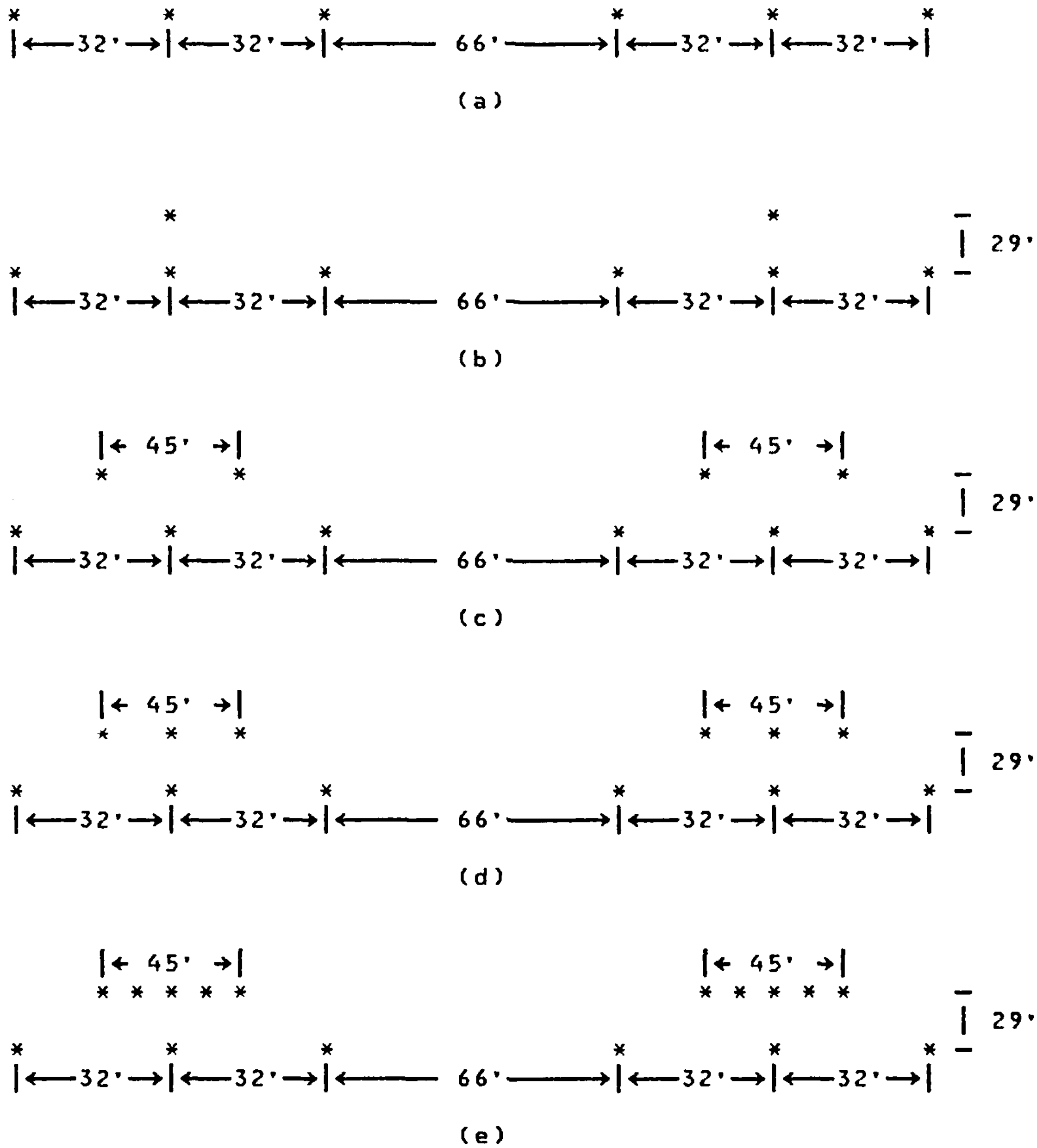


Figure 4.4 Double Horizontal Circuit Configurations: (a) No OHGW, (b) One OHGW, (c) Two OHGW, (d) Three OHGW, (e) Five OHGW

abca'b'c'; this circuit is made up of two identical circuits positioned side by side. Although represented as single conductors at each position, the double circuit is also developed using bundled conductors. The development starts with a single, three phase circuit using bundled conductors. The 6x6 matrix of that circuit is then reduced to lessen the amount of conductors per position. This reduced system is then mirrored across a vertical axis to create the double circuit shown. Even though the double circuit contains 12 conductors, it is drawn schematically with six by mathematically considering each bundle as one conductor. Figure 4.4(a) in matrix form yields a 6x6 matrix $P_{abca'b'c'}$.

$$P_{abca'b'c'} = \left[\begin{array}{ccc|ccc} P_{aa} & P_{ab} & P_{ac} & P_{aa'} & P_{ab'} & P_{ac'} \\ P_{ba} & P_{bb} & P_{bc} & P_{ba'} & P_{bb'} & P_{bc'} \\ P_{ca} & P_{cb} & P_{cc} & P_{ca'} & P_{cb'} & P_{cc'} \\ \hline P_{a'a} & P_{a'b} & P_{a'c} & P_{a'a'} & P_{a'b'} & P_{a'c'} \\ P_{b'a} & P_{b'b} & P_{b'c} & P_{b'a'} & P_{b'b'} & P_{b'c'} \\ P_{c'a} & P_{c'b} & P_{c'c} & P_{c'a'} & P_{c'b'} & P_{c'c'} \end{array}\right] \tag{4.13}$$

Equation (4.13) is divided into four sections to illustrate how it is assembled. The top left and bottom right quarters of the potential matrix are identical and represent the original reduced form of the bundled conductor. The remainder of the matrix represents the mutual potential terms that occur between the two halves of the circuit.

As in the case of a single circuit, once a potential matrix is compiled the unbalance analysis is routine. Equation (4.13) must be inverted to find the phase capacitance of the system. Anderson [4] shows that this capacitance matrix can be made into a smaller equivalent by summing the four equal (in size) sections of the phase capacitance (see equations (3.23) and (3.25)). Once done, the symmetrical components are found from the phase capacitance. The sequence capacitance contains all the information necessary to calculate the unbalance of the circuit.

Again using 500 MCM, the electrostatic unbalance of a double horizontal circuit without overground ground wires is calculated. First a potential matrix like equation (4.13) is computed.

$$P_{abca'b'c'} = \left[\begin{array}{ccc|ccc} 75.2204 & 20.6142 & 13.1843 & 6.7798 & 5.1709 & 4.0438 \\ 20.6161 & 75.2204 & 20.6161 & 9.1696 & 6.7798 & 5.1709 \\ 13.1843 & 20.6161 & 75.2204 & 12.9605 & 9.1696 & 6.7798 \\ \hline 6.7798 & 9.1696 & 12.9605 & 75.2204 & 20.6142 & 13.1843 \\ 5.1709 & 6.7798 & 9.1696 & 20.6161 & 75.2204 & 20.6161 \\ 4.0438 & 5.1709 & 6.7798 & 13.1843 & 20.6161 & 75.2204 \end{array}\right] \tag{4.14}$$

Notice the symmetry that exists in equation (4.14). The top left and the bottom right quadrants are exactly those of equation (4.6) with the possible exception of some rounding differences. The potential matrix must be inverted

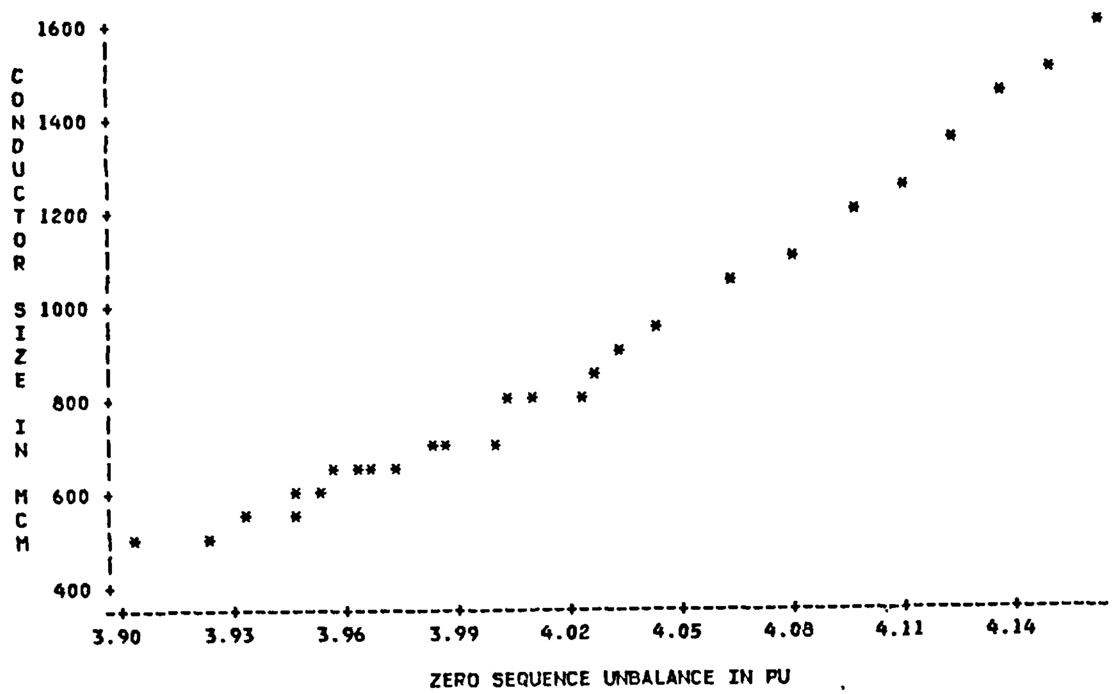
directly to find the phase capacitance of the system. If properly done, the phase capacitance of the entire system is also a 6x6 matrix. Reducing this matrix as described by Anderson [4] will yield a 3x3 equivalent matrix of phase capacitance.

$$C_{abc} = \begin{bmatrix} -2.8473E-02 & -7.9725E-03 & -4.8616E-03 \\ -7.9732E-03 & 2.9813E-02 & -7.9732E-03 \\ -4.8613E-03 & -7.9739E-03 & 2.8473E-02 \end{bmatrix} \qquad (4.15)$$

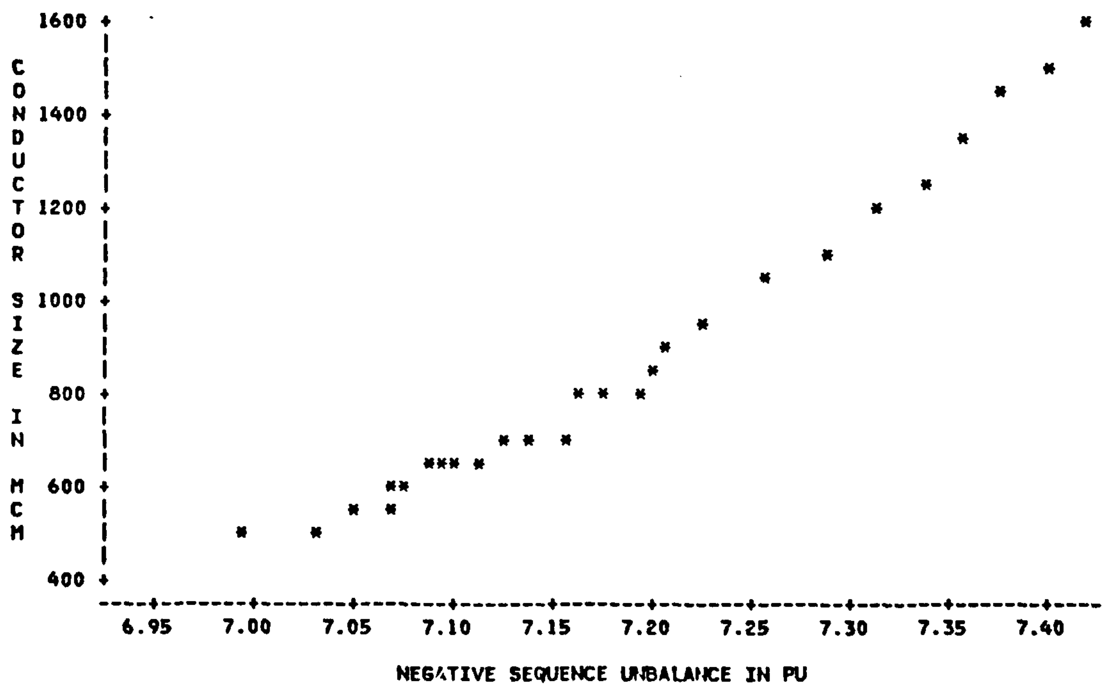
All that is left is the transformation to symmetrical components. Including the 100 mile length factor, the C_{012} of the double horizontal circuit with 500 MCM conductor is the 3x3 matrix shown below.

$$C_{012} = \begin{bmatrix} 1.5048 & .0295 & .0295 \\ +J0.0 & +J.0511 & -J.0511 \\ & & \\ .0295 & 3.5856 & -.1261 \\ -J.0511 & -J0.0 & -J.2183 \\ & & \\ .0295 & -.1261 & 3.5856 \\ +J.0511 & +J.2183 & +J0.0 \end{bmatrix} \qquad (4.16)$$

With the information from above the actual per unit unbalance is found with the following relationships.



(a)



(b)

Figure 4.5 Wire Size In MCM Versus Unbalance for Double Horizontal Circuit Without OHGW for (a) Zero Sequence, (b) Negative Sequence.

$$d_0 = -\frac{C_{01}}{C_{00}} = 3.9233 \angle -120.00° \% \tag{4.17}$$

and

$$d_2 = -\frac{C_{21}}{C_{11}} = 7.0314 \angle -60.00° \% \tag{4.18}$$

Above, d_0 and d_2 are found as per cent or per unit quantities for 500 MCM. When all 27 sizes are checked for unbalance the graphs of Figure 4.5 can be made. The same trend is exhibited that was seen on the previous unbalance plots. The trend is that the unbalance in both negative and zero sequences increases with increased wire size. Additionally, the negative sequence unbalance is the larger of the two unbalance factors.

4.6 Double Vertical Circuit Without OHGW

The methods for calculating zero and negative sequence electrostatic unbalances in a double vertical circuit are identical to that of its horizontal counterpart of Section 4.5. However, because the geometry of the circuit is radically different, it follows that the results (ie. per unit unbalance) should also be changed. Figure 4.6 depicts the five double circuit arrangements investigated with a

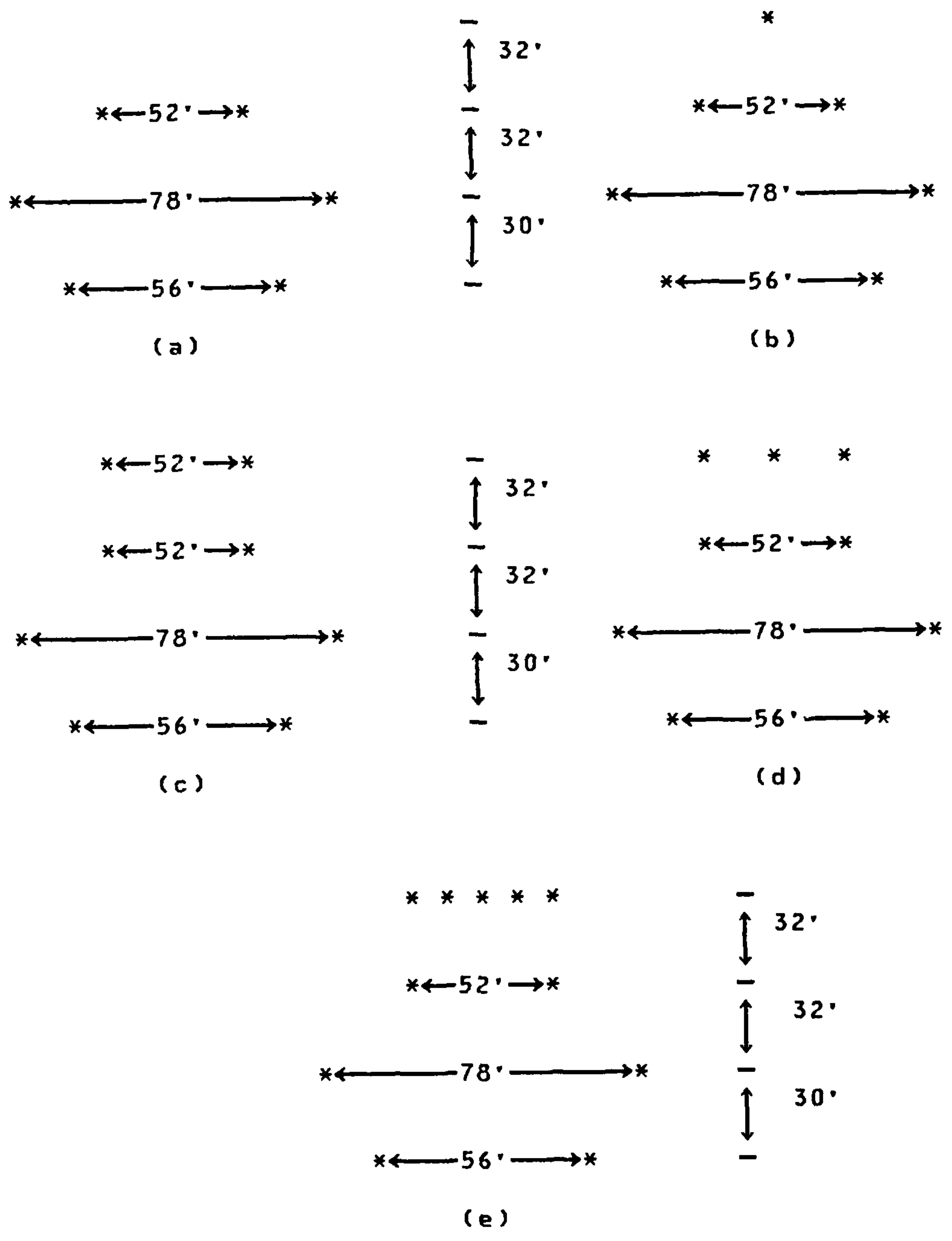


Figure 4.6 Double Vertical Circuit Configurations: (a) No OHGW, (b) One OHGW, (c) Two OHGW, (d) Three OHGW, (e) Five OHGW

vertical tower. In the no overhead ground wire case 4.6(a), 27 MCM sizes were again tested and unbalances were calculated. For consistency, 500 MCM is the conductor that will be illustrated in this section. First the potential matrix of the double circuit had to be found using the previous methods of equation (3.1) and (3.2).

$$P_{abca'b'c'} = \left[\begin{array}{ccc|ccc} 75.8712 & 18.3998 & 9.8622 & 16.0231 & 10.8494 & 7.3962 \\ 18.3998 & 71.8642 & 14.7135 & 10.8494 & 8.5229 & 6.8619 \\ 9.8622 & 14.7135 & 66.0534 & 7.3963 & 6.8619 & 6.9473 \\ \hline 16.0231 & 10.8494 & 7.3963 & 75.8712 & 18.3998 & 9.8622 \\ 10.8494 & 8.5229 & 6.8619 & 18.3998 & 71.8642 & 14.7135 \\ 7.3962 & 6.8619 & 6.9473 & 9.8622 & 14.7135 & 66.0534 \end{array}\right] \tag{4.19}$$

As in the horizontal configuration, the original vertical circuit potential matrix has symmetry. The "original" refers to the 6x6 potential matrix of the double circuit that is assembled from the reduced bundled conductor scheme. The top left and the bottom right corners of this matrix are identical and equal to the reduced bundle matrix. Since capacitance has an inverse relationship to potential, the matrix is inverted to find the phase capacitance matrix of the total circuit. Sequence capacitance is the desirable form, so the phase capacitance must be transformed. When done, the sequence capacitance matrix of equation (4.20) is found for 500 MCM.

$$C_{012}=\begin{bmatrix} 1.5978 & -.1312 & -.1312 \\ +J0.0 & +J.1508 & -J.1508 \\ & & \\ -.1312 & 3.4488 & -.2323 \\ -J.1598 & +J0.0 & -J.2529 \\ & & \\ -.1312 & -.2323 & 3.4488 \\ +J.1508 & +J.2529 & -J0.0 \end{bmatrix} \tag{4.20}$$

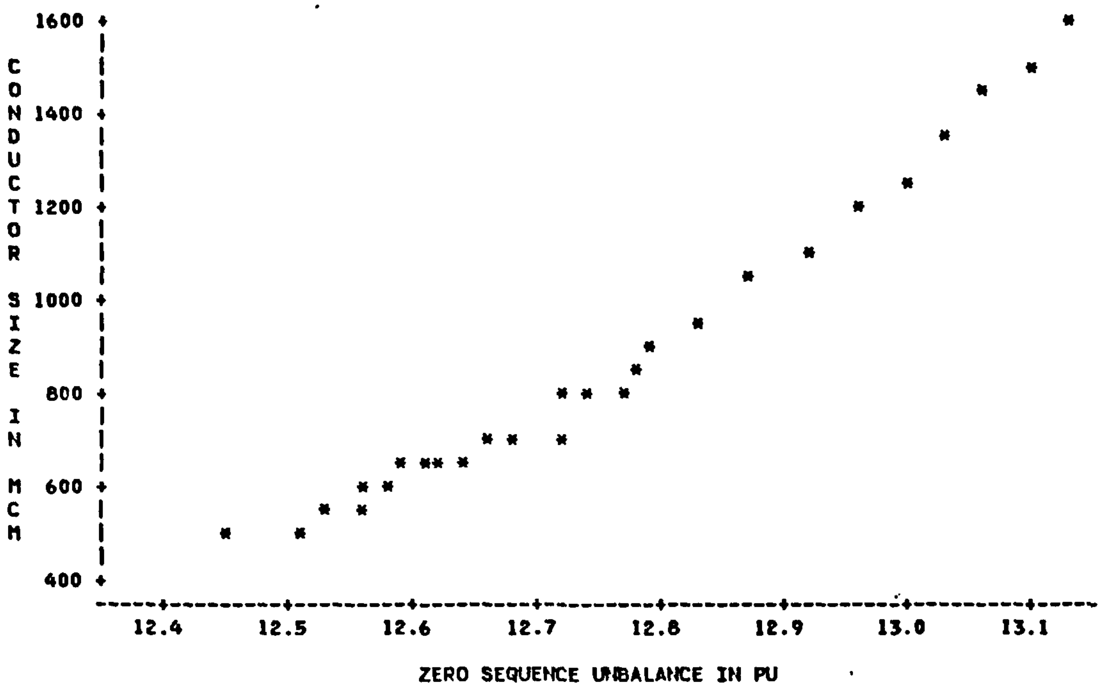
The useful portions of equation (4.20) are the elements (0,0), (0,1), (1,1), and (2,1). Finding the unbalances again means finding the ratios of these specific elements. The zero and negative sequence unbalance factors are shown below.

$$d_0=-\frac{C_{01}}{C_{00}} = 12.5076 \;\angle\underline{-48.97°}\% \tag{4.21}$$

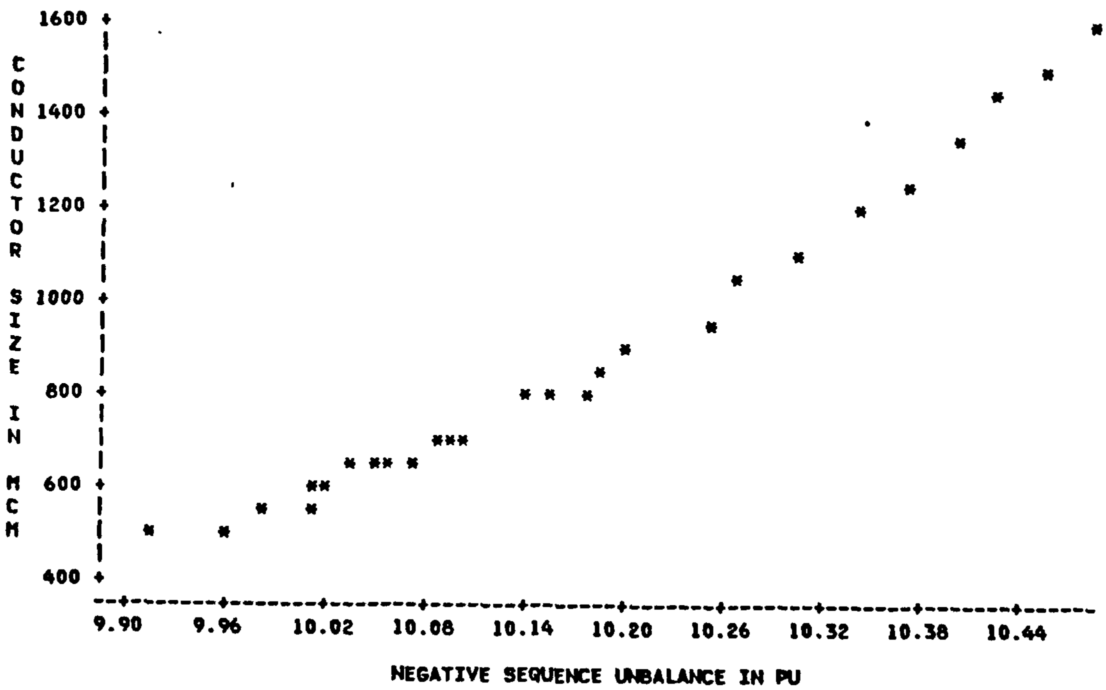
and

$$d_2=-\frac{C_{21}}{C_{11}}= 9.9575 \;\angle\underline{-47.44°}\% \tag{4.22}$$

The complete picture of all the unbalance magnitudes for all the wire sizes is shown in Figure 4.7. Consistency is again displayed as the unbalance in both negative and zero sequence rises when the MCM number is raised. When comparing negative to zero sequence it is seen that the zero sequence is the larger of the two unbalances.



(a)



(b)

Figure 4.7 Wire Size In MCM Versus Unbalance for Double Vertical Circuit Without OHGW for (a) Zero Sequence, (b)Negative Sequence

4.7 Double Horizontal Circuit With OHGW

Thus far no mention has been given to the practical case of when overhead ground wires exist in the system. For the horizontal double circuit, one, two, three, and five ground wires were mathematically added to the circuit of Section 4.5 and unbalances were determined.

The process of finding a negative or zero sequence unbalance is changed slightly with the addition of ground wires. If a single ground wire were added to each side of the double circuit of Figure 4.6(a) the circuit of Figure 4.6(b) would result. For horizontal configurations, the number of ground wires above each half of the circuit is the number of ground wires the circuit is thought to have. In other words, a two ground wire system actually has four ground wires overhead. The reason for this factor in the number of ground wires is the distance that occurs between the two halves of the circuit. Since the circuit is so spread out it is necessary to center the grounds above the circuit conductors. However, by so doing, it is impossible to get an odd number of overhead grounds without losing symmetry. It will later be seen that the vertical system does not follow the same pattern for counting the number of ground wires.

For all ground wire cases the ground wire will be 7-strand, 3/8" EBB steel conductor.

The addition of two ground wires (considered the one ground circuit), increases the size of the original potential matrix equation (4.14) by two rows and two columns. Using standard 500 MCM ASCR, the new potential matrix can be calculated as follows.

$P_{abca'b'c'uw}=$

$$\left[\begin{array}{cccccc|cc}
75.2204 & 20.6161 & 13.1843 & 6.7798 & 5.1709 & 4.0438 & 18.7411 & 5.9560 \\
20.6161 & 75.2172 & 20.6161 & 9.1696 & 6.7798 & 5.1709 & 23.0808 & 7.6120 \\
13.1843 & 20.6161 & 75.2204 & 12.9605 & 9.1696 & 6.7798 & 18.7411 & 9.9506 \\
6.7798 & 9.1696 & 12.9605 & 75.2204 & 20.6161 & 13.1843 & 9.9506 & 18.7411 \\
5.1709 & 6.7798 & 9.1696 & 20.6161 & 75.2172 & 20.6161 & 7.6130 & 23.0808 \\
4.0438 & 5.1709 & 6.7798 & 13.1843 & 20.6161 & 75.2204 & 5.9560 & 18.7411 \\
\hline
18.7411 & 23.0808 & 18.7411 & 9.9506 & 7.6130 & 5.9560 & 108.4910 & 8.9194 \\
5.9560 & 7.6130 & 9.9506 & 18.7411 & 23.0808 & 18.7411 & 8.9194 & 108.4910
\end{array}\right] \tag{4.23}$$

The additional rows and columns are a result of the ground wires interacting with the basic double circuit (basic refers to the double circuit without OHGW). Potential is formed between the ground wires and the actual phase conductors. Kron reduction must be performed on equation (4.23) to eliminate the excess rows and columns but not the effects of the ground wires on the circuit. What Kron reduction does is shrink the matrix down to a smaller form without negating the effects of every component of that matrix. The Kron reduced version of equation (4.23) representing Figure 4.5(b) is shown on the next page.

$P_{abca'b'c'}=$

$$\begin{bmatrix} 71.8021 & 16.3943 & 9.6023 & 4.3265 & 2.9358 & 2.2671 \\ 16.3948 & 70.0038 & 16.1830 & 6.1020 & 3.9691 & 2.9358 \\ 9.6023 & 16.1830 & 71.3267 & 9.8428 & 6.1020 & 4.3265 \\ 4.3265 & 6.1020 & 9.8428 & 71.3267 & 16.1830 & 9.6023 \\ 2.9358 & 3.9691 & 6.1020 & 16.1830 & 70.0038 & 16.3948 \\ 2.2671 & 2.9358 & 4.3265 & 9.6023 & 16.3948 & 71.8021 \end{bmatrix} \tag{4.24}$$

Notice that Kron reduction reduces each self and mutual potential term of the double circuit independent of the ground wires. Once the total circuit potential matrix is Kron reduced, it is possible to continue the unbalance analysis as was done for the ungrounded systems. Equation (4.24) must be inverted to find the phase capacitance. The phase capacitance matrix must be divided into four equally sized sections then added. Finally the phase to sequence conversion must be performed .

$$C_{012}=\begin{bmatrix} 1.7680 & .0186 & .0186 \\ +J0.0 & +J.0321 & -J.0321 \\ .0186 & 3.5882 & -.1266 \\ -J.0321 & +J0.0 & -J.2193 \\ .0186 & -.1266 & 3.5882 \\ +J.0321 & +J.2193 & -J0.0 \end{bmatrix} \tag{4.25}$$

The unbalance fractions are taken from the C_{012} matrix of equation (4.25). The negative sequence is the same ratio whether the system is grounded or not.

$$d_0 = \frac{C_{01}}{C_{11}} = 1.0342 \angle \underline{60.00°} \% \qquad (4.26)$$

However, if overhead ground wires are used, the zero sequence unbalance formula must be modified [4].

$$d_2 = \frac{C_{21}}{C_{11}} = 7.0572 \angle \underline{-60.00°} \% \qquad (4.27)$$

If all 27 wire sizes of Table 4.3 are included in the above analysis, a graph showing wire size as a function of unbalance can be made. Figure 4.8 shows this graph.

The same analysis techniques can be used on a double horizontal circuit if more than one overhead ground wire is used. First the potential matrix must be found, then inverted, multiplied by 100, and finally converted to symmetrical components for the actual unbalance fraction. The unbalance results of multi-ground systems are shown on Figure 4.9 for the two ground case; and in Table A.3, and A.4 for the three and five ground cases.

Again the results follow a pattern. The unbalance for either case increases with increased MCM conductor size. This is true for the zero, one, two, three, and five ground wire systems tested in both zero and negative sequence. Also, a: in the majority of the circuits thus far, the negative sequence unbalance is much larger

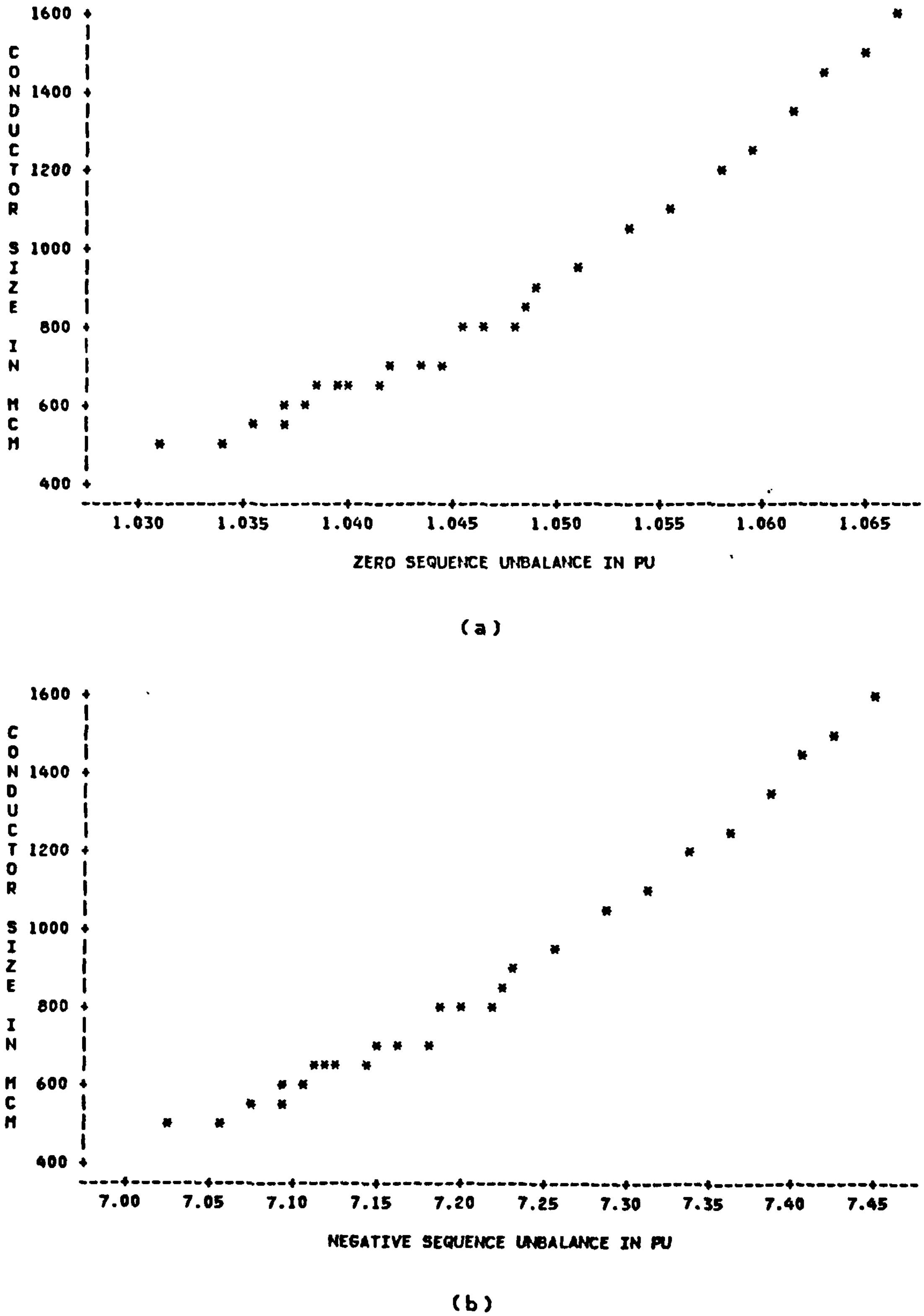
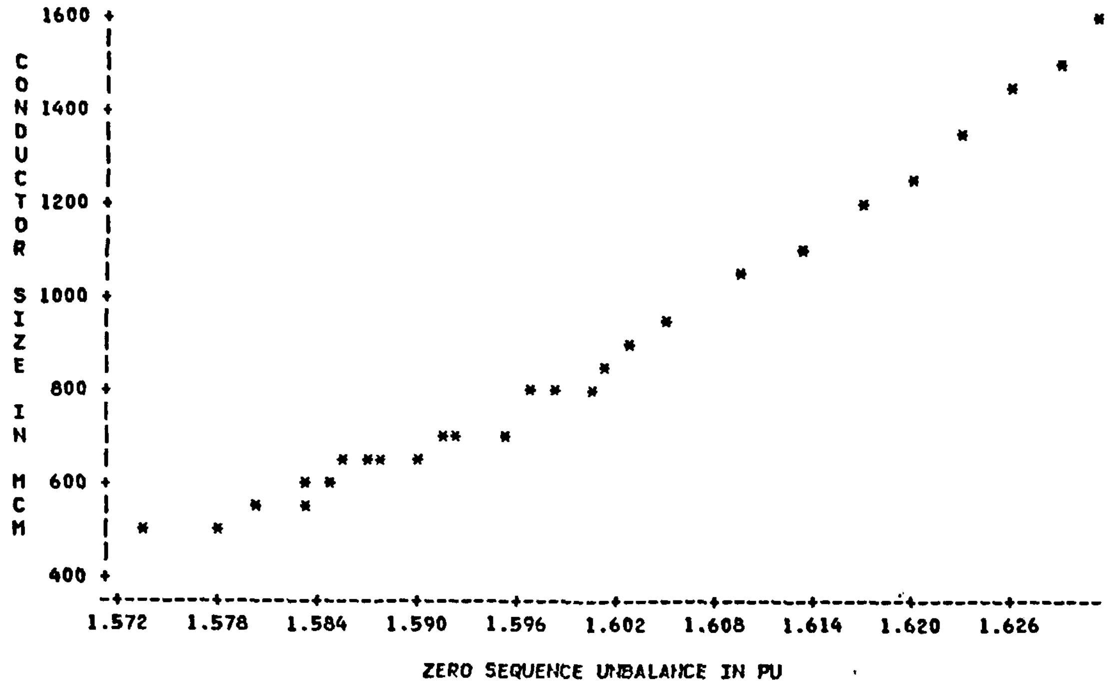
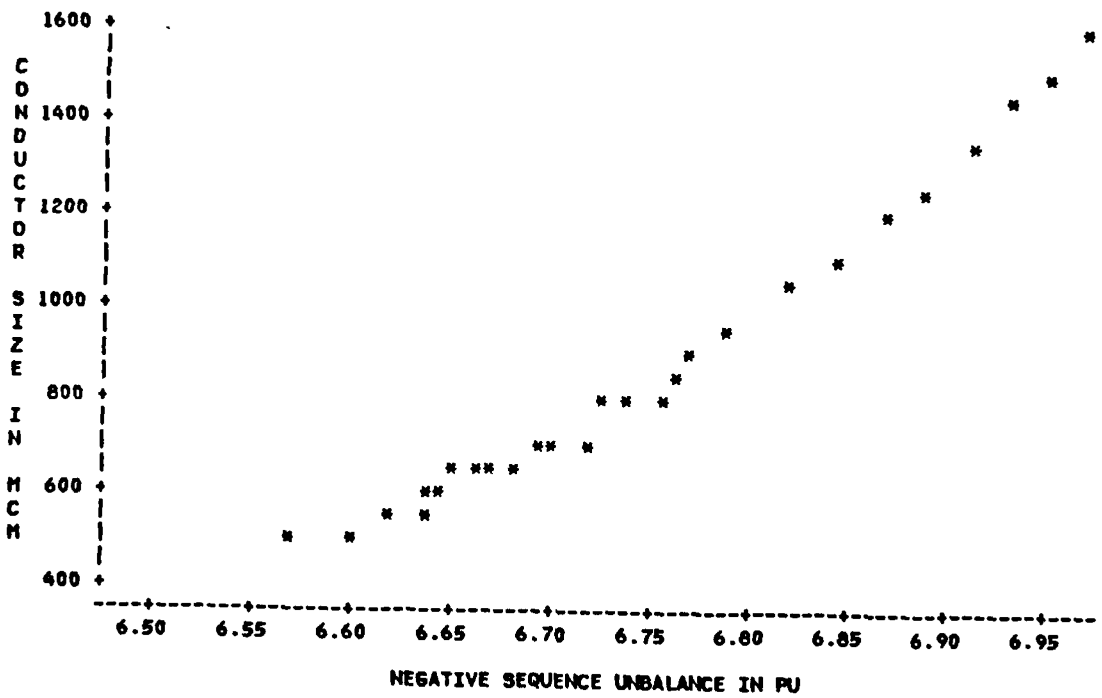


Figure 4.8 Wire Size In MCM Versus Unbalance for Double Horizontal Circuit With One OHGW for (a) Zero Sequence (b) Negative Sequence



(a)



(b)

Figure 4.9 Wire Size In MCM Versus Unbalance for Double Horizontal Circuit With Two OHGW for (a) Zero Sequence, (b) Negative Sequence

than the zero sequence. The difference is as much as four times more. This is the norm that is developing in this research. Only in two configurations was the zero sequence unbalance the larger of the two factors. That was the result of an asymmetrical system and no ground wires. When ground wires are added, their effects far outweigh the effect of the asymmetrical system and the unbalance is dominated by the ground wire effect. This ground wire effect does little to change the negative sequence and betters the zero sequence. In other words, to improve the zero sequence unbalance of a horizontal system, ground wires can be added.

4.8 Vertical Double Circuit With OHGW

The analysis of a vertical double circuit with one or more overhead ground wires is identical to that of the horizontal case. For clarity, the procedure will be outlined and some important relationships will be listed. Starting with the addition of one ground wire to the basic vertical circuit (see Figure 4.9(b)), the potential matrix before any reduction is the 7x7 matrix of equation(4.28) for the 500 MCM conductor. The size difference between the vertical and the horizontal representation is an additional row and column caused by the ground wires. Remembering that two ground wires, one over each half circuit, is labeled a one-ground wire system will eliminate any questions raised over the matrix size difference.

$P_{abca'b'c'uu}=$

$$\left[\begin{array}{cccccc|c}
75.8712 & 18.3998 & 9.8622 & 16.0231 & 10.8494 & 7.3962 & 19.9220 \\
18.2998 & 71.8642 & 14.7135 & 10.8494 & 8.5229 & 6.8619 & 11.8000 \\
9.8622 & 14.7135 & 66.0535 & 7.3963 & 6.8619 & 6.9473 & 7.0357 \\
16.0231 & 10.8494 & 7.3963 & 75.8712 & 18.3998 & 9.8622 & 19.9220 \\
10.8494 & 8.5229 & 6.8619 & 18.3998 & 71.8642 & 14.7135 & 11.8000 \\
7.3962 & 6.8619 & 6.9473 & 9.8622 & 14.7135 & 66.0535 & 7.0357 \\
\hline
19.9220 & 11.8000 & 7.0357 & 19.9220 & 11.8000 & 7.0357 & 109.2470
\end{array}\right] \tag{4.28}$$

The effects of the ground wire must again be incorporated into a smaller matrix, therefore, Kron reduction is done to the matrix of equation (4.28).

Once reduced, the matrix is ready to be inverted into phase capacitance form. As in previous cases, the phase capacitance matrix is subdivided into four square matrix sections. These sections are added for a new, more compact, phase capacitance. The sequence capacitance is found by a phase to sequence conversion and individual elements of the sequence matrix are used for unbalance calculations.

$$C_{012}=\begin{bmatrix}
\begin{array}{l}1.7101\\+J0.0\end{array} & \begin{array}{l}-.0776\\+J.1378\end{array} & \begin{array}{l}-.0776\\-J.1378\end{array} \\[2ex]
\begin{array}{l}-.0776\\-J.1378\end{array} & \begin{array}{l}3.4759\\+J0.0\end{array} & \begin{array}{l}-.2082\\-J.2406\end{array} \\[2ex]
\begin{array}{l}-.0776\\+J.1378\end{array} & \begin{array}{l}-.2082\\+J.2406\end{array} & \begin{array}{l}3.3759\\-J0.0\end{array}
\end{bmatrix} \tag{4.29}$$

To find the negative sequence unbalance for 500 MCM conductor, the negative of the ratio of c_{21} to c_{11} is found.

$$d_2 = -\frac{C_{21}}{C_{11}} = 9.1528 \underline{/-49.12°} \% \tag{4.30}$$

Since overhead ground wires are now being considered, the zero sequence is a different ratio than before. Zero sequence electrosatic unbalance for 500 MCM with ground wires is the ratio of c_{01} to c_{11}.

$$d_0 = \frac{C_{01}}{C_{11}} = 4.5496 \underline{/\ 119.39°} \% \tag{4.31}$$

If the other 26 ACSR sizes are likewise analyzed, a plot of the data can be made. Figure 4.10 shows the zero and negative sequence plots of wire size versus per cent unbalance.

Two, three, and five ground wire systems were similarly investigated. Each additional ground wire adds one row and one column to the basic matrix of equation (4.19). The process for finding the zero and negative sequence unbalance factors remain the same regardless of the number of overhead ground wires.

First the potential matrix of the system with ground wires is found. The system is then Kron reduced, inverted,

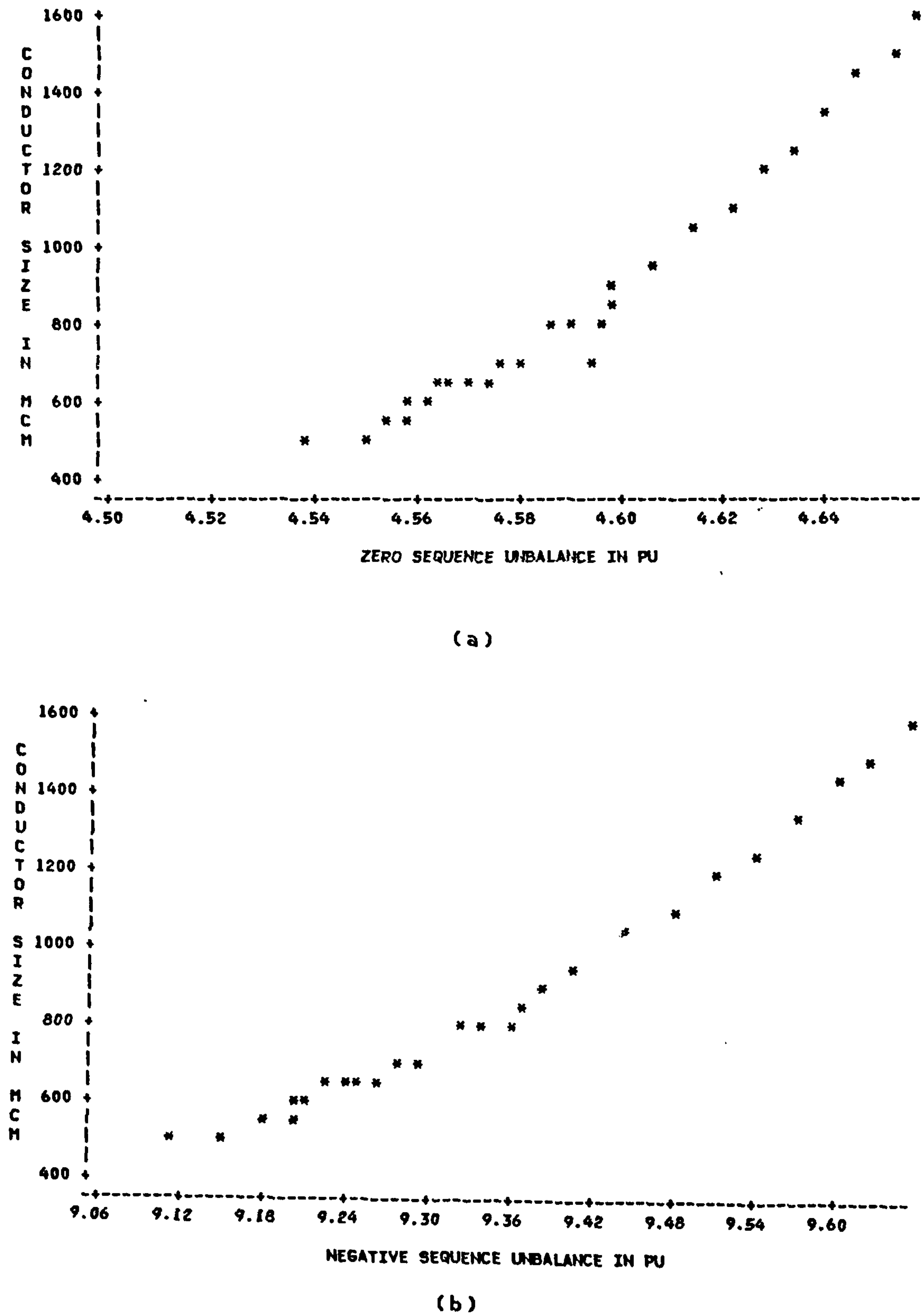
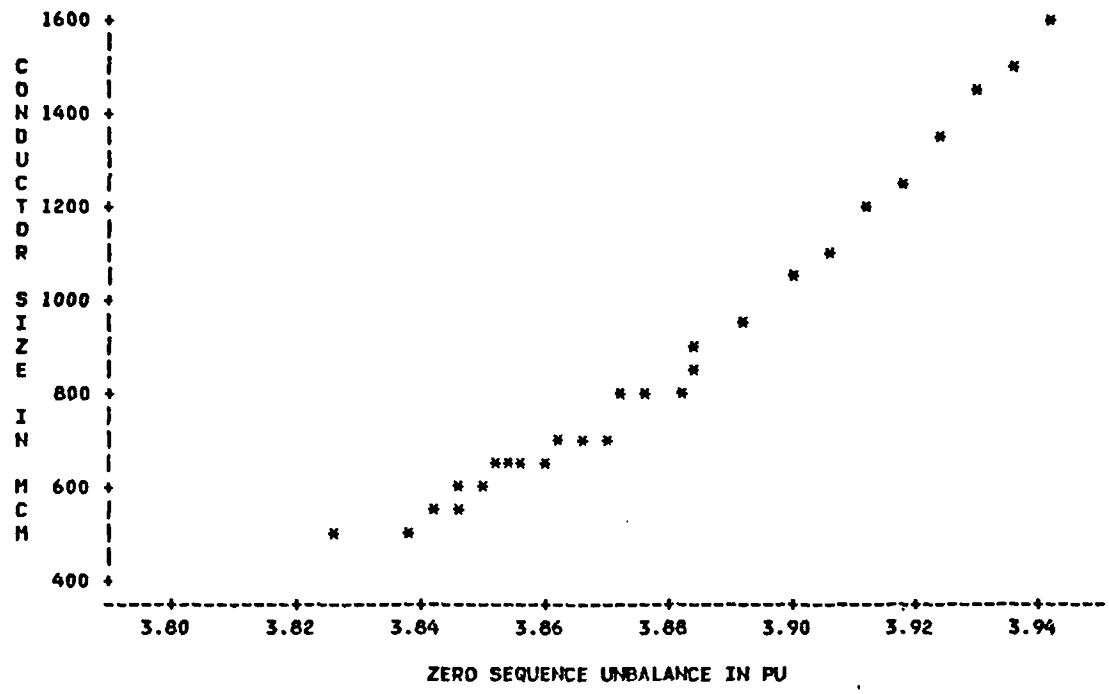
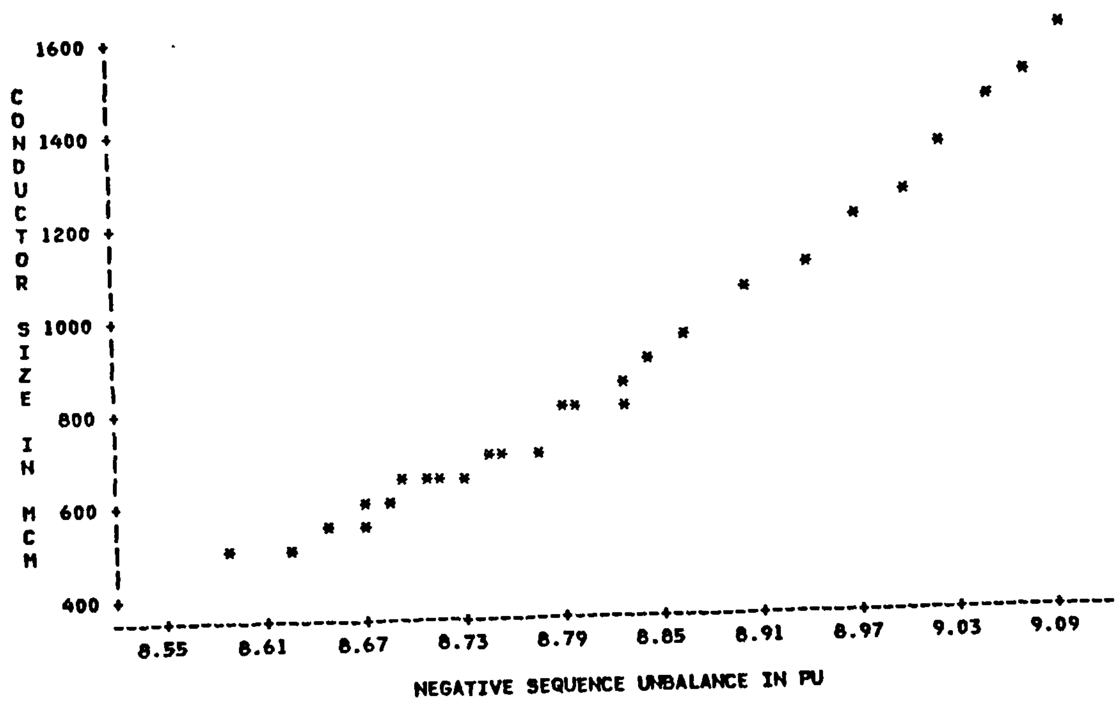


Figure 4.10 Wire Size In MCM Versus Unbalance for Double Vertical Circuit With One OHGW for (a) Zero Sequence, (b) Negative Sequence



(a)



(b)

Figure 4.11 Wire Size In MCM Versus Unbalance for Double Vertical Circuit With Two OHGW for (a) Zero Sequence, (b) Negative Sequence

subdivided for addition, added, converted to sequence capacitance, then ratioed. All 27 ACSR conductor sizes must be done in the same manner. When the two wire system was tested as stated above, the graphs on Figure 4.11 where made. Data for the three ground and five ground wire cases appear in the appendix as Table A.6 and A.7.

4.9 Twisted Circuits

It is possible to improve the unbalance characteristics of a system by altering the conductor position on the tower. Without changing the spacing between, or the ASCR size of the conductor, the unbalance can be lowered or raised simply by interchanging the conductor positions on the tower. The changes can come by partially or totally transposing both the horizontal or the vertical circuit. It is possible to modify the conductor arrangement by using the circuit operators derived by Anderson [4]. One of the operators used to modify the conductor positions is the twist function [4]. When used, the twist function will interchange the location of any two conductors specified.

$$T_{012}=\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \qquad (4.32)$$

The other important operator that will mathematically modify a circuit is rotation [4].

$$R_{012} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & a^2 \end{bmatrix} \tag{4.33}$$

where $a = 1\underline{/120^\circ}$

and $a^2 = 1\underline{/240^\circ}$

It was shown by Haj-mohamadi [11] that a total of 12 variations of a basic circuit exist through use of the twist and rotation functions. Table 4.4 shows the 12 shifting matrices necessary to obtain the different conductor arrangements. Using the operators of equation (4.32) and (4.33) a 6x6 matrix is assembled as shown in Table 4.4. Each matrix of the table is made up of four 3x3 matrices. A null matrix is designated by the zero and an identity matrix is shown by the U. When the matrix for the basic circuit ($P_{abca'b'c'}$) is premultiplied by and postmultiplied by one of the 12 new operator matrices, a new conductor configuration results. The center of Table 4.4 shows the possible conductor positions.

4.10 Horizontal Circuit Twisted

The basic horizontal double circuit is again considered; this time the 12 positions will be tested. For comparison, 500 MCM ASCR will be used. Testing other wire sizes was not deemed necessary since the main factor influencing any unbalance changes would be conductor geometry.

Table 4.4 Twelve Possible Conductor Arrangements

$$\begin{bmatrix} U & 0 \\ 0 & U \end{bmatrix}$$
(BASE)

$$\begin{bmatrix} U & 0 \\ 0 & R_{012} \end{bmatrix}$$
(2)

$$\begin{bmatrix} U & 0 \\ 0 & R^2{}_{012} \end{bmatrix}$$
(3)

$$\begin{bmatrix} U & 0 \\ 0 & T_{012} \end{bmatrix}$$
(4)

$$\begin{bmatrix} U & 0 \\ 0 & R_{012}T_{012} \end{bmatrix}$$
(5)

CASE	TOWER POSITION					
	1	2	3	1'	2'	3'
base	a	b	c	a'	b'	c'
2	a	b	c	b'	c'	a'
3	a	b	c	c'	a'	b'
4	a	b	c	a'	c'	b'
5	a	b	c	b'	a'	c'
6	a	b	c	c'	b'	a'
7	a	c	b	a'	b'	c'
8	a	c	b	b'	c'	a'
9	a	c	b	c'	a'	b'
10	a	c	b	a'	c'	b'
11	a	c	b	b'	a'	c'
12	a	c	b	c'	b'	a'

$$\begin{bmatrix} U & 0 \\ 0 & R^2{}_{012}T_{012} \end{bmatrix}$$
(6)

$$\begin{bmatrix} T_{012} & 0 \\ 0 & U \end{bmatrix}$$
(7)

$$\begin{bmatrix} T_{012} & 0 \\ 0 & R_{012} \end{bmatrix}$$
(8)

$$\begin{bmatrix} T_{012} & 0 \\ 0 & R^2{}_{012} \end{bmatrix}$$
(9)

$$\begin{bmatrix} T_{012} & 0 \\ 0 & T_{012} \end{bmatrix}$$
(10)

$$\begin{bmatrix} T_{012} & 0 \\ 0 & R_{012}T_{012} \end{bmatrix}$$
(11)

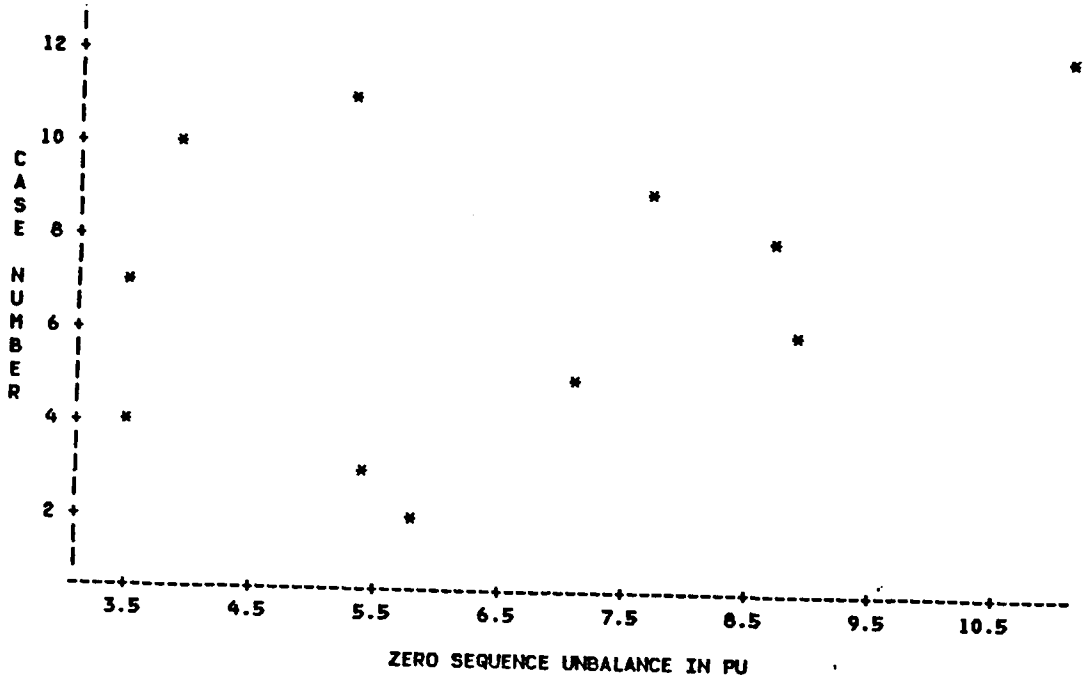
$$\begin{bmatrix} T_{012} & 0 \\ 0 & R^2{}_{012}T^2{}_{012} \end{bmatrix}$$
(12)

Starting with the no-ground circuit, the potential matrix was found as before. The principal difference between this circuit and the other is the conductor sequence. Since the sequence has nothing to do with the analysis performed everything will be done as usual. Therefore, as before, the matrix is inverted to find capacitance. This capacitance is manipulated by the shifting operators to obtain every possible conductor position. After the capacitance is pre and post multiplied by the shifting matrix it is reduced and converted to symmetrical components for unbalance analysis. The unbalance analysis proceeds as it did for all other cases.

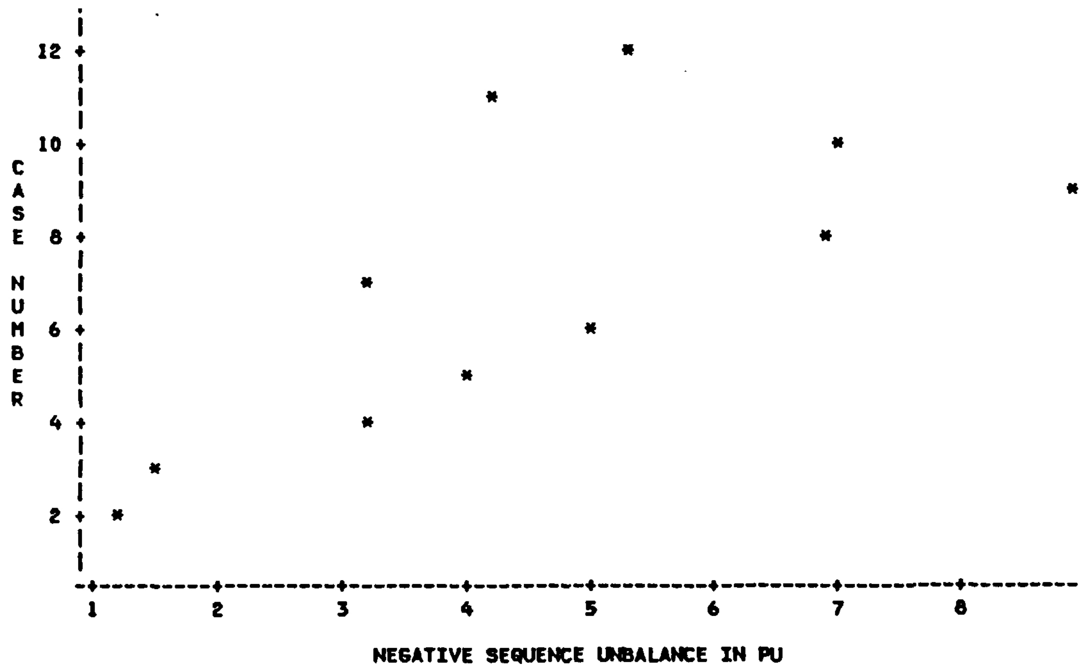
Again, it is important to mention that all reductions, inversions, and ratios are the same for this condition as in past circuits with one exception. The shifting operator is used to modify the previous circuits tested to give them new conductor arrangements.

When ground wires are added the procedure changes in that the circuit must be Kron reduced before being inverted. After Kron reduction the procedure continues as if no ground wires were present.

The unbalance for negative and zero sequence was found for all 12 conductor positions using 500 MCM ACSR using circuits with zero, one, two, three, and five overhead ground wires. Results of the zero, one, and two OHGW cases are plotted on Figures 4.12, 4.13, and 4.14. These plots are of the case number versus the unbalance in per cent.

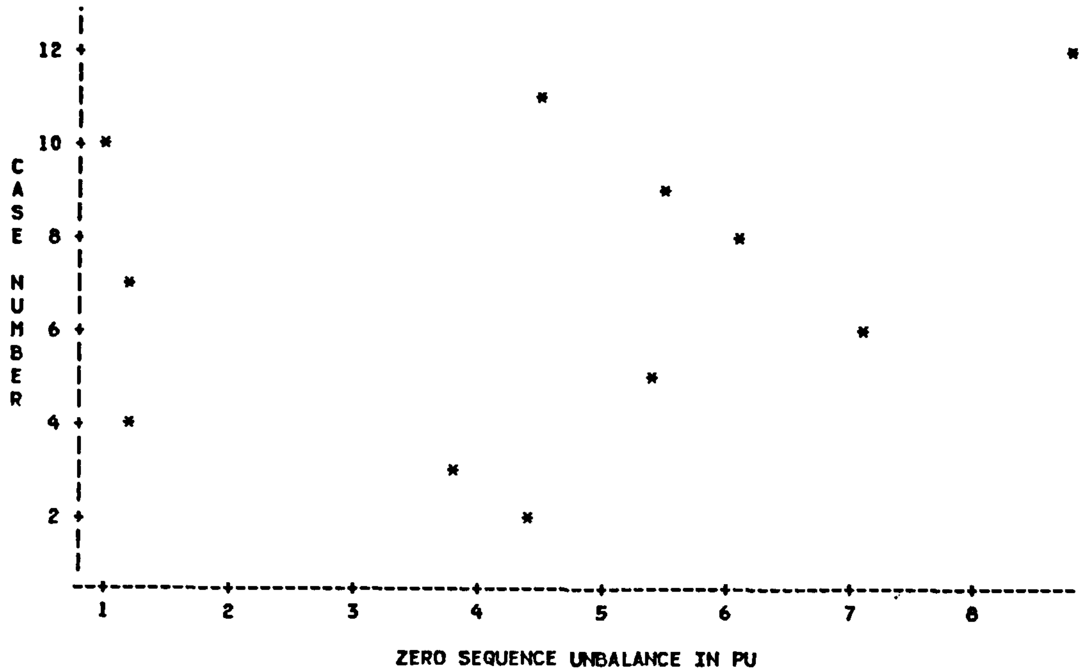


(a)

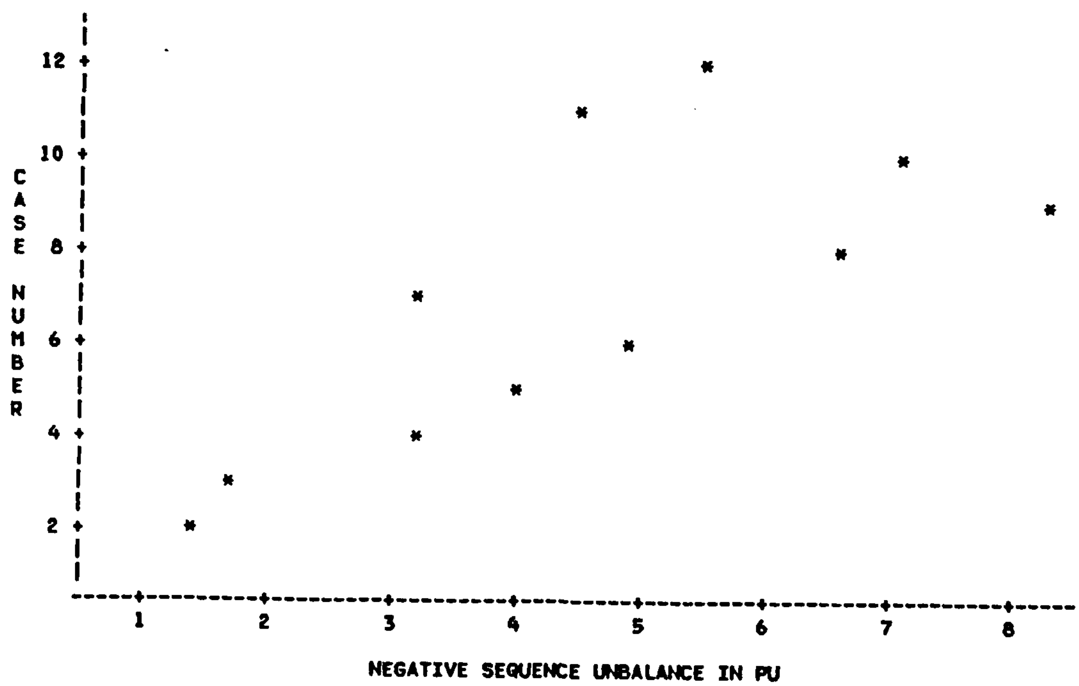


(b)

Figure 4.12 Wire Size In MCM Versus Unbalance for Horizontal Twisted Circuit With No OHGW for (a) Zero Sequence, (b) Negative Sequence

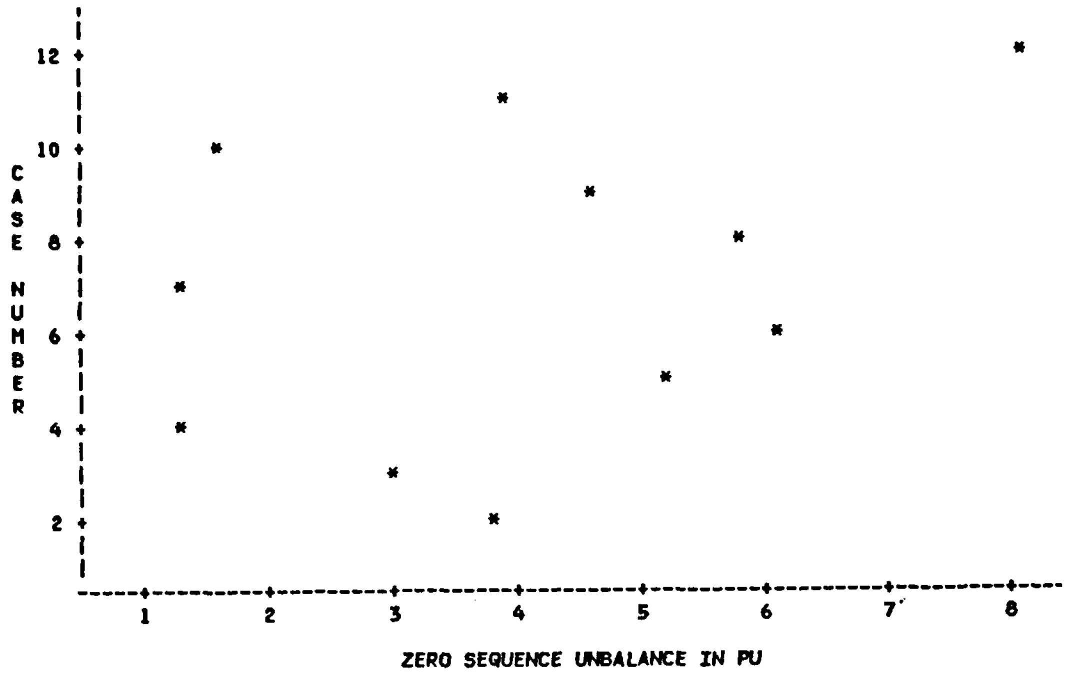


(a)

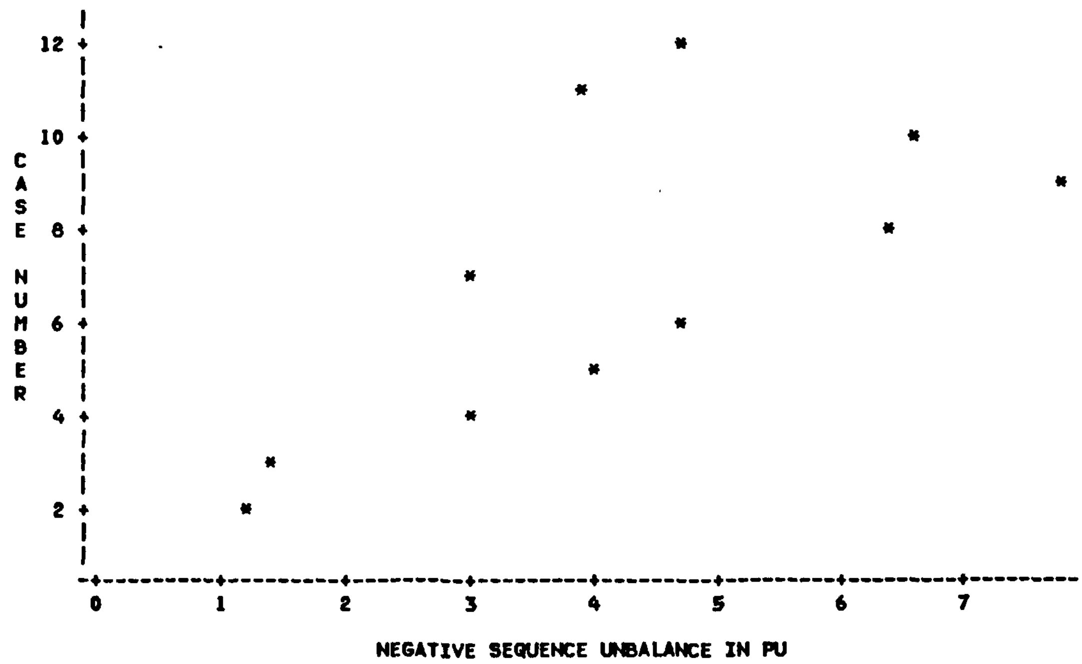


(b)

Figure 4.13 Wire Size In MCM Versus Unbalance for Horizontal Twisted Circuit With One OHGW for (a) Zero Sequence, (b) Negative Sequence



(a)



(b)

Figure 4.14 Wire Size In MCM Versus Unbalance for Horizontal Twisted Circuit With Two OHGW for (a) Zero Sequence, (b) Negative Sequence

The case number refers to the number of one of the 12 conductor positions shown on Table 4.4. The randomness of which these plots occur as a result of the randomness at which the conductors were originally twisted and rotated. No methodical sequence was used to change the positions of the wires. The only stipulation was that all 12 possible conductor arrangements were tested. It is seen that the optimum conductor arrangement for both zero and negative sequence is case #7.

There is another way to compare the data appears in Table 4.5 and 4.6. This shows how, for a given conductor arrangement, the unbalances vary with the addition of overhead ground wires. Examining these tables reveals that the unbalance varies with the number of ground wires. Also, the conductor sequence with the overall lowest zero sequence unbalance is case #7. Sequence case #2 gives the best (lowest) negative sequence unbalance.

4.11 Vertical Circuit Twisted

The vertical double circuit is almost a repetition of the horizontal. Naturally the original P matrix is unique, but the steps that yield the actual unbalances are identical in form.

For the vertical circuit, 500 MCM wire was again used. All 12 conductor positions were tested, and unbalances found for each. The same randomness of results that existed

Table 4.5 Horizontal Double Circuit Rotation Unbalance Data

Group	Number Grounds	Per-Cent Sequence Unbalance	
		Zero	Negative
Base	0	3.9244	7.0316
	1	1.0341	7.0567
	2	1.5781	6.6018
	3	1.4674	6.5949
	5	0.8197	6.5857
#2	0	5.7826	1.2097
	1	4.4197	1.3838
	2	3.8041	1.1567
	3	4.0572	1.1345
	5	4.0734	1.5634
#3	0	5.4308	1.5455
	1	3.7982	1.7152
	2	2.9562	1.4088
	3	2.5190	1.3537
	5	2.0076	1.6719
#4	0	3.5280	3.1800
	1	1.2441	3.2357
	2	1.2582	3.0243
	3	1.2165	2.9579
	5	0.9621	3.0760
#5	0	7.0512	4.0255
	1	5.4457	3.9985
	2	5.1867	3.9505
	3	5.0789	3.9431
	5	5.0286	3.9577
#6	0	8.[illegible]449	5.0414
	1	7.0721	4.8555
	2	6.0651	4.7200
	3	5.4819	4.6459
	5	4.7172	4.4803

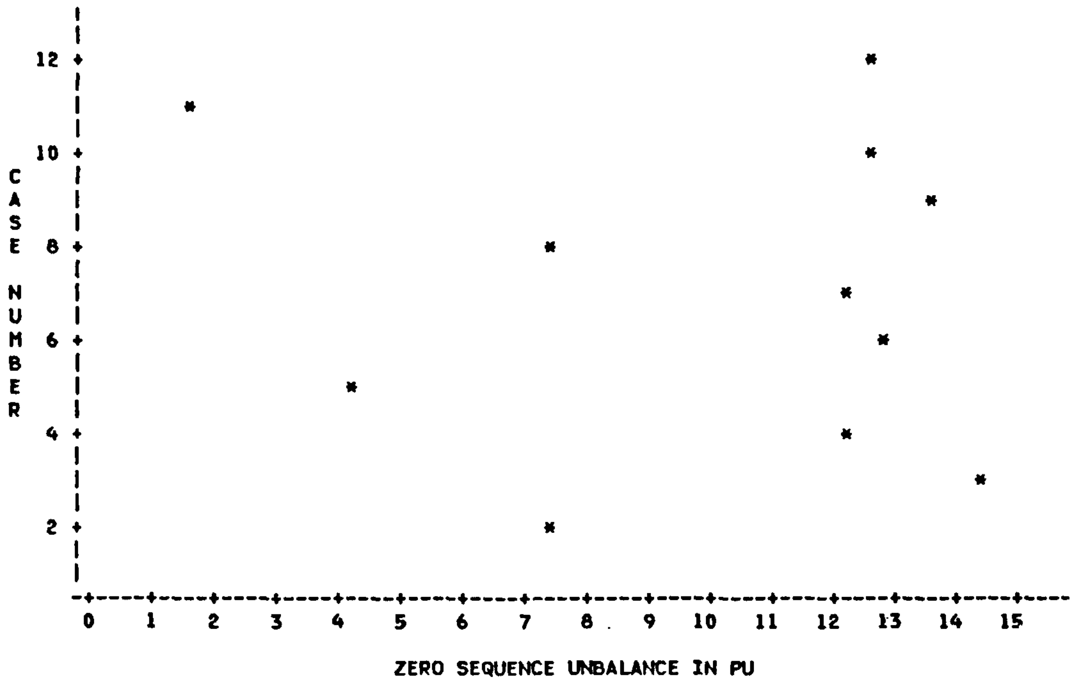
Table 4.6 Horizontal Double Circuit Rotation Unbalance Data

Group	Number Grounds	Per-Cent Sequence Unbalance Zero	Negative
#7	0	3.5280	3.1800
	1	1.2441	3.2357
	2	1.2582	3.0243
	3	1.2165	2.9579
	5	0.9620	3.0760
#8	0	8.7415	6.8997
	1	6.0989	6.6437
	2	5.8174	6.3558
	3	5.7895	6.3236
	5	5.4544	5.9427
#9	0	6.6769	8.9116
	1	5.4947	8.2975
	2	4.6154	7.7916
	3	3.8936	7.6244
	5	3.2289	7.1235
#10	0	3.9244	7.0316
	1	1.0341	7.0567
	2	1.5781	6.6018
	3	1.4674	6.5949
	5	0.8963	6.5857
#11	0	5.3452	4.2024
	1	4.5051	4.5052
	2	3.8770	3.8771
	3	4.0288	3.9497
	5	4.2082	4.2105
#12	0	11.1484	5.3449
	1	8.7707	5.5361
	2	8.0713	4.6821
	3	7.1642	4.6980
	5	6.0206	4.8949

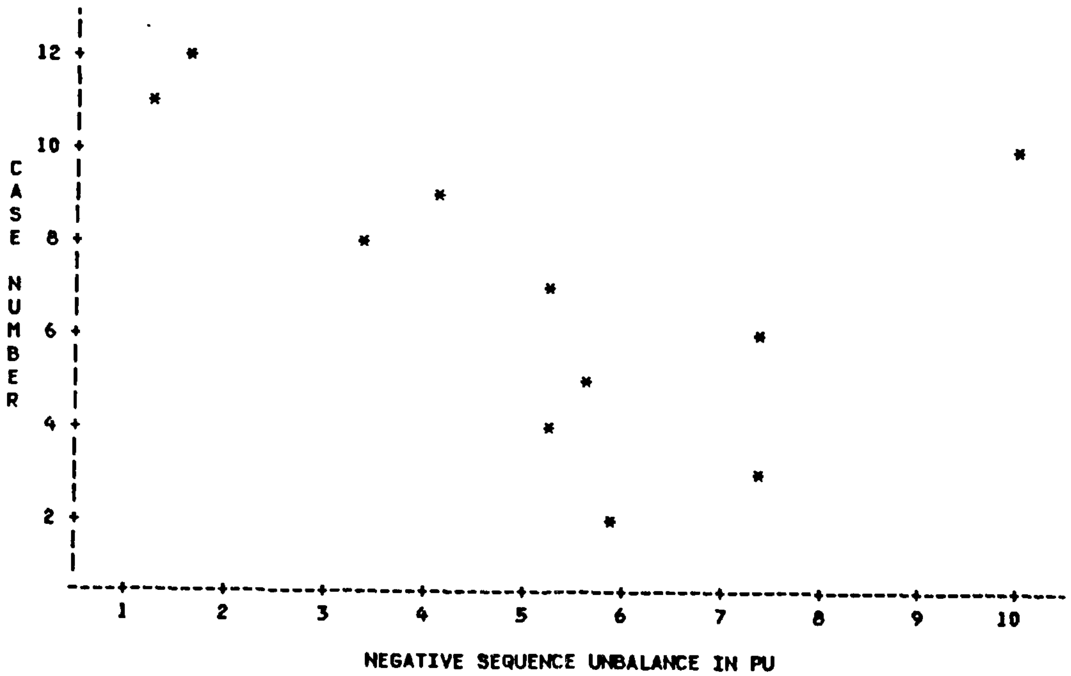
in the horizontal analysis also exists here as the conductor position is not one of a methodical derivation.

Figure 4.15 shows the random distribution of the unbalance as a function of conductor position for the no-ground case. As before, one, two, three, and five ground wires were added to the no-ground circuit on separate tests to check the unbalances of both negative and zero sequence. For the one and two ground cases, results were plotted and shown on Figure 4.16 and 4.17 for the negative and zero sequence runs. Notice that all graphs still have that random quality about them. Also note that although the graphs are identical in spacing, the abscissa has entirely different units for each circuit. It is seen from an examination of the three plots and the tables in the appendix that the best arrangement for zero sequence and the negative sequence is case #11. The reader is referred to Table 4.4 for sequencing information about that case.

For a total view of how the number of ground wires effects a given conductor sequence, Tables 4.6 and 4.7 have been included. On the tables, the 500 MCM ACSR wire is analyzed for the vertical double circuit.



(a)



(b)

Figure 4.15 Wire Size In MCM Versus Unbalance for Vertical Twisted Circuit With No OHGW for (a) Zero Sequence, (b) Negative Sequence

AD-A160 742 ELECTROSTATIC UNBALANCES OF TRANSMISSION LINES(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH J NOWIKOWSKI AUG 85 AFIT/CI/NR-85-102T 2/2

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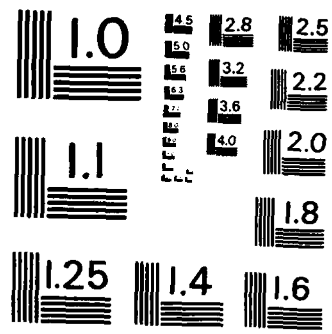
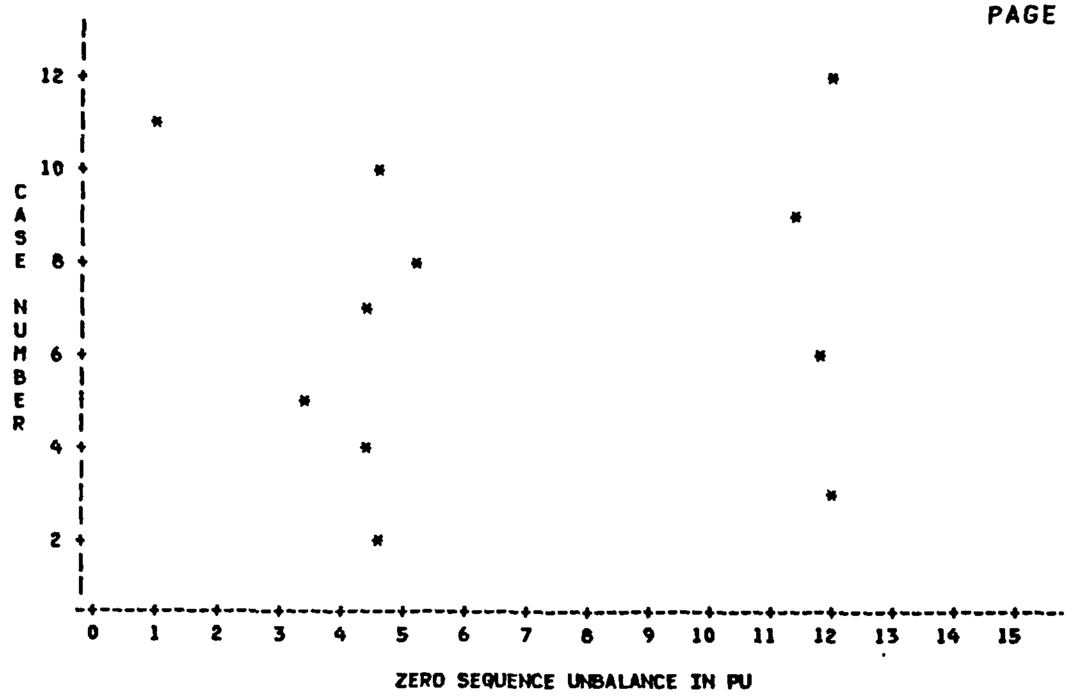
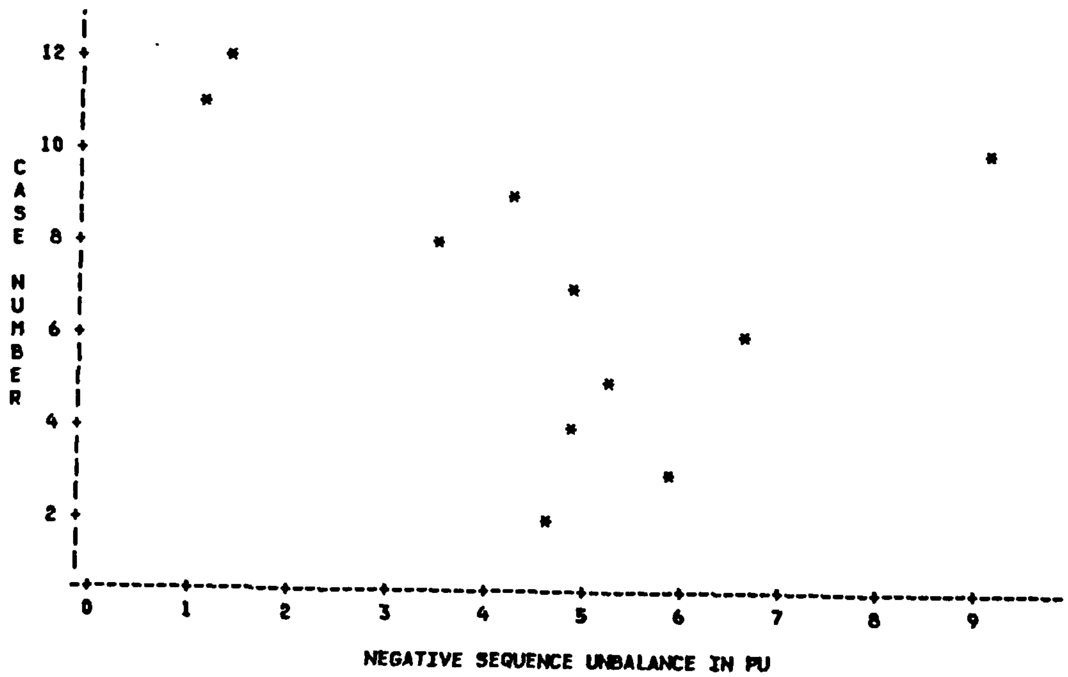


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

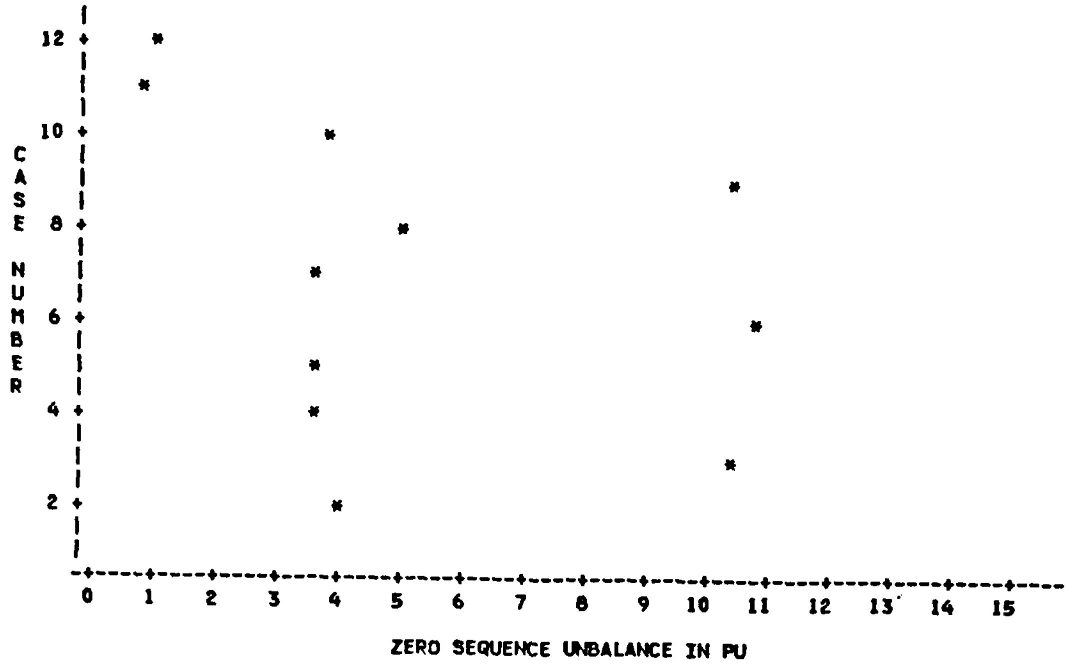


(a)

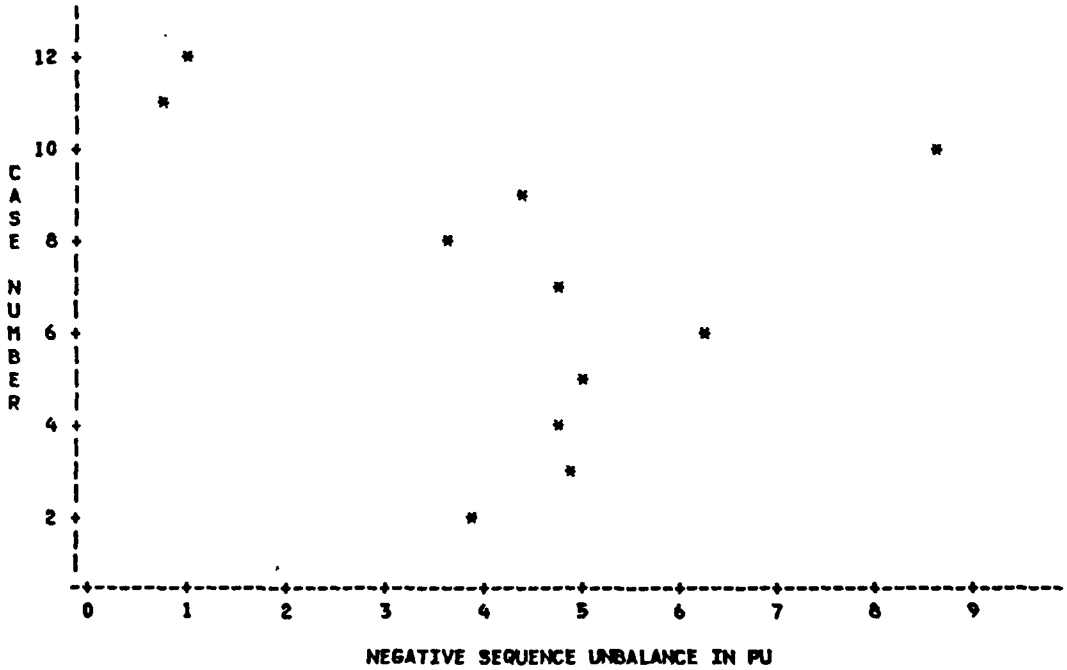


(b)

Figure 4.16 Wire Size In MCM Versus Unbalance for Vertical Twisted Circuit With One OHGW for (a) Zero Sequence, (b) Negative Sequence



(a)



(b)

Figure 4.17 Wire Size In MCM Versus Unbalance for Vertical Twisted Circuit With Two OHGW for (a) Zero Sequence, (b) Negative Sequence

Table 4.7 Vertical Double Circuit Rotation Unbalance Data

Group	Number Grounds	Per-Cent Sequence Unbalance Zero	Per-Cent Sequence Unbalance Negative
Base	0	12.5076	9.9576
	1	4.5496	9.1528
	2	3.8379	8.6245
	3	3.4879	8.2238
	5	3.3479	7.8336
#2	0	7.3773	5.8468
	1	4.6756	4.6756
	2	3.9240	3.9240
	3	3.3182	3.3182
	5	2.7195	2.7038
#3	0	14.3225	7.3777
	1	11.9558	5.8137
	2	10.4244	4.8290
	3	9.3203	4.0653
	5	8.0867	3.1965
#4	0	12.2764	5.2832
	1	4.4601	4.9008
	2	3.6889	4.7128
	3	3.1452	4.5226
	5	2.6242	4.3616
#5	0	4.1243	5.6129
	1	3.4642	5.2001
	2	3.6053	4.9778
	3	3.6834	4.7972
	5	3.7551	4.6433
#6	0	12.8779	7.3251
	1	11.8449	6.6510
	2	10.7078	6.2871
	3	9.8740	5.9946
	5	8.9226	5.6760

Table 4.8 Vertical Double Circuit Rotation Unbalance Data

Group	Number Grounds	Per-Cent Sequence Unbalance Zero	Per-Cent Sequence Unbalance Negative
#7	0	12.2764	5.2832
	1	4.4601	4.9008
	2	3.6889	4.7128
	3	3.1452	4.5226
	5	2.6242	4.3616
#8	0	7.3246	3.3313
	1	5.2002	3.4641
	2	4.9779	3.6052
	3	4.7973	3.6934
	5	4.6584	3.7515
#9	0	13.5740	4.1240
	1	11.3820	4.2569
	2	10.3498	4.4008
	3	9.6208	4.4807
	5	8.7624	4.5996
#10	0	12.5077	9.9576
	1	4.5496	9.1528
	2	3.8379	8.6246
	3	3.4879	8.2237
	5	3.3479	7.8336
#11	0	1.5970	1.2774
	1	1.0707	1.0707
	2	0.7858	0.7858
	3	0.6649	0.6649
	5	0.4636	0.4866
#12	0	12.6688	1.5967
	1	11.9072	1.3269
	2	11.4635	0.9666
	3	11.1335	0.8301
	5	10.7370	0.6283

CHAPTER 5

CONCLUSION

5.1 Introduction

Although this research has included many different cases, the conclusions fall into three basic categories. These categories are: the effects of the conductor size, number of over head ground wires, and the conductor-tower position on the magnitude of the electrostatic unbalance. In all, 27 separate ASCR wire designations were tested for each circuit conceived.

The single circuit was used as the building block for the basic double circuit, ground wires were then added for the most complex configurations. The effects of ground wires were tested on the basic circuit. Both the horizontal and vertical versions of the double circuit were examined for all 27 wire sizes on each of the zero, one, two, three, and five overhead ground wire systems.

Finally, testing was done on the effects of moving the conductors from their normal sequence positions. Here only the 500 MCM wire was used, but 12 different sequence arrangements were researched on circuits having zero, one, two, three, and five ground wires.

5.2 Effects Of Wire Size

The trends are quite clear. In every circuit where the conductor size was the variable and all else was held constant, it was found that the unbalance increased with increased wire size. Starting with 477 MCM and testing each common size up to 1590 MCM, both the zero and the negative sequence unbalance increased with a larger conductor diameter. Increased wire size results in a larger self-potential, the diagonal of the potential matrix. This self-potential is the dominate factor in determining the size of an electrostatic unbalance.

When comparing the zero sequence to the negative sequence it is found that the negative sequence is, in general, larger. A few isolated cases occurred where the zero sequence was larger. However, this difference did not follow a trend nor was the magnitude of the difference substantial. Therefore a conclusion that the negative sequence unbalance is larger than the zero sequence is appropriate. This conclusion is independent of the number of ground wires present in the circuit.

5.3 Effects Of The Number Of OHGW

When the number of overhead ground wires was varied and the conductor size and position was held constant the results were also decisive. Instead of looking at a variety of wire sizes, a variety of sequences (See Table 4.4) were explored. Twelve different sequences each with none, one

two, three, and five ground wires were tested with 500 MCM conductor. A comparison shows the relationship between unbalance, either zero or negative, and the number of ground wires. Because this trend is examined for all possible sequences, the results are more meaningful.

For the vertical circuit (double), as the number of ground wires are added, the zero and negative sequence unbalance decreases. In every case, the unbalance with no ground wires was the greatest. Some varying did occur in a few sequence configurations but a trend is clearly shown.

For the horizontal circuits a trend exists but not as distinct as for the vertical case. Again, the no ground case has the highest unbalance for both zero and negative sequence. However, in some cases the unbalance reaches its low point before all the ground wires have been added. In other words, the best unbalance performance may not be with the most ground wires.

5.4 Effects Of Twisting And Rotatimg

Twisting and rotating the phase conductors clearly has an effect on the sequence unbalance as shown in Chapter 4. There does seem to be a best sequence for each zero, and negative sequence unbalance, and there is also a worst. The optimum sequence arrangements were outlined in Chapter 4. Also, the appendix contains a best to worst order of the sequence arrangements for both horizontal and vertical circuit configurations.

5.5 Conclusion

After all the research and analysis is it obvious that a circuit unbalance can be altered, for better or worst, by varying the circuit geometry. If the goal is to improve the zero and negative sequence characteristics of a circuit, as it should be, three things should be tried.

One, reduce the conductor size if possible. Two, add overhead ground wires until the circuit performance is acceptable. Finally, use the circuit sequence from Table 4.4 that best corrects the unbalances needed.

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APPENDIX

Table A.1 Single Horizontal Circuit Unbalance Data

Conductor Size In MCM	Strand		Per-Cent Sequence Unbalance	
	Al	St	Zero	Negative
1 590 000	54	19	5.0388/-120.0°	9.2753/ -60.0°
1 510 000	54	19	5.0242/-120.0°	9.2507/ -60.0°
1 431 000	54	19	5.0079/-120.0°	9.2230/ -60.0°
1 351 000	54	19	4.9922/-120.0°	9.1966/ -60.0°
1 272 000	54	19	4.9757/-120.0°	9.1687/ -60.0°
1 192 000	54	19	4.9581/-120.0°	9.1390/ -60.0°
1 133 000	54	19	4.9391/-120.0°	9.1068/ -60.0°
1 033 000	54	7	4.9184/-120.0°	9.0718/ -60.0°
954 000	54	7	4.8962/-120.0°	9.0340/ -60.0°
900 000	54	7	4.8809/-120.0°	9.0081/ -60.0°
874 000	54	7	4.8740/-120.0°	8.9965/ -60.0°
795 000	54	7	4.8480/-120.0°	8.9523/ -60.0°
795 000	26	7	4.8560/-120.0°	8.9658/ -60.0°
795 000	30	19	4.8707/-120.0°	8.9909/ -60.0°
715 000	54	7	4.8205/-120.0°	8.9056/ -60.0°
715 000	26	7	4.8278/-120.0°	8.9179/ -60.0°
715 000	30	19	4.8421/-120.0°	8.9423/ -60.0°
666 600	54	7	4.8022/-120.0°	8.8745/ -60.0°
636 000	54	7	4.7895/-120.0°	8.8530/ -60.0°
636 000	26	7	4.7971/-120.0°	8.8657/ -60.0°
636 000	30	19	4.8120/-120.0°	8.8913/ -60.0°
605 000	54	7	4.7767/-120.0°	8.8310/ -60.0°
605 000	26	7	4.7844/-120.0°	8.8442/ -60.0°
556 000	26	7	4.7624/-120.0°	8.8068/ -60.0°
556 000	30	7	4.7767/-120.0°	8.8310/ -60.0°
500 000	30	7	4.7502/-120.0°	8.7860/ -60.0°
477 000	26	7	4.7244/-120.0°	8.7420/ -60.0°

Table A.2 Single Vertical Circuit Unbalance Data

Conductor Size In MCM	Strand		Per-Cent Sequence Unbalance	
	Al	St	Zero	Negative
1 590 000	54	19	8.5261/ -67.4°	7.7694/ -47.4°
1 510 000	54	19	8.5041/ -67.4°	7.7492/ -47.4°
1 431 000	54	19	8.4766/ -67.4°	7.7266/ -47.4°
1 351 000	54	19	8.4519/ -67.4°	7.7042/ -47.4°
1 272 000	54	19	8.4269/ -67.4°	7.6813/ -47.4°
1 192 000	54	19	8.3998/ -67.3°	7.6564/ -47.4°
1 133 000	54	19	8.3720/ -67.3°	7.6287/ -47.4°
1 033 000	54	7	8.3401/ -67.3°	7.5995/ -47.4°
954 000	54	7	8.3055/ -67.3°	7.5679/ -47.4°
900 000	54	7	8.2783/ -67.3°	7.5491/ -47.5°
874 000	54	7	8.2713/ -67.3°	7.5366/ -47.5°
795 000	54	7	8.2288/ -67.2°	7.5001/ -47.5°
795 000	26	7	8.2432/ -67.3°	7.5109/ -47.5°
795 000	30	19	8.2662/ -67.3°	7.5320/ -47.5°
715 000	54	7	8.1865/ -67.2°	7.4615/ -47.5°
715 000	26	7	8.1995/ -67.2°	7.4710/ -47.5°
715 000	30	19	8.2201/ -67.2°	7.4910/ -47.5°
666 600	54	7	8.1598/ -67.2°	7.4348/ -47.5°
636 000	54	7	8.1401/ -67.2°	7.4168/ -47.5°
636 000	26	7	8.1501/ -67.2°	7.4283/ -47.5°
636 000	30	19	8.1751/ -67.2°	7.4487/ -47.5°
605 000	54	7	8.1185/ -67.2°	7.3993/ -47.5°
605 000	26	7	8.1316/ -67.2°	7.4085/ -47.5°
556 000	26	7	8.0980/ -67.2°	7.3783/ -47.5°
556 000	30	7	8.1185/ -67.2°	7.3993/ -47.5°
500 000	30	7	8.0798/ -67.2°	7.3577/ -47.5°
477 000	26	7	8.0367/ -67.1°	7.3246/ -47.5°

Table A.3 Double Horizontal Circuit With Three OHGW Unbalance Data

Conductor Size In MCM	Strand		Per-Cent Sequence Unbalance	
	Al	St	Zero	Negative
1 590 000	54	19	1.5198	6.0636
1 510 000	54	19	1.5172	6.9451
1 431 000	54	19	1.5143	6.9242
1 351 000	54	19	1.5115	6.9043
1 272 000	54	19	1.5086	6.8833
1 192 000	54	19	1.5054	6.8608
1 133 000	54	19	1.5020	6.8366
1 033 000	54	7	1.4982	6.8102
954 000	54	7	1.4942	6.7817
900 000	54	7	1.4914	6.7622
874 000	54	7	1.4902	6.7534
795 000	54	7	1.4854	6.7202
795 000	26	7	1.4869	6.7304
795 000	30	19	1.4896	6.7493
715 000	54	7	1.4804	6.6850
715 000	26	7	1.4817	6.6943
715 000	30	19	1.4843	6.7126
666 600	54	7	1.4770	6.6616
636 000	54	7	1.4747	6.6454
636 000	26	7	1.4760	6.6549
636 000	30	19	1.4788	6.6742
605 000	54	7	1.4723	6.6288
605 000	26	7	1.4737	6.6388
556 000	26	7	1.4696	6.6106
556 000	30	7	1.4723	6.6288
500 000	30	7	1.4674	6.5949
477 000	26	7	1.4626	6.5618

Table A.4 Double Horizontal Circuit With Five OHGW Unbalance Data

Conductor Size In MCM	Strand		Per-Cent Sequence Unbalance	
	Al	St	Zero	Negative
1 590 000	54	19	.8507	6.9539
1 510 000	54	19	.8492	6.9354
1 431 000	54	19	.8475	6.9145
1 351 000	54	19	.8458	6.8947
1 272 000	54	19	.7967	6.9420
1 192 000	54	19	.8422	6.8513
1 133 000	54	19	.8401	6.8271
1 033 000	54	7	.8379	6.8007
954 000	54	7	.8355	6.7722
900 000	54	7	.8339	6.7528
874 000	54	7	.8331	6.7440
795 000	54	7	.8303	6.7108
795 000	26	7	.8312	6.7210
795 000	30	19	.8328	6.7398
715 000	54	7	.8273	6.6756
715 000	26	7	.8281	6.6849
715 000	30	19	.8297	6.7033
666 600	54	7	.8253	6.6522
636 000	54	7	.8240	6.6360
636 000	26	7	.8248	6.6456
636 000	30	19	.8264	6.6648
605 000	54	7	.8225	6.6196
605 000	26	7	.8234	6.6294
556 000	26	7	.8210	6.6013
556 000	30	7	.8225	6.6196
500 000	30	7	.8197	6.5857
477 000	26	7	.8168	6.5523

Table A.5 Ground Wire Effect For Three Arbitrary Sizes (Horizontal)

MCM Size	Number Grounds	Per-Cent Sequence Unbalance Zero	Negative
1590 MCM	0	12.1328	10.4832
	1	4.6589	9.6492
	2	3.9420	9.0996
	3	3.5722	8.6805
	5	3.4556	8.2745
874 MCM	0	12.7773	10.1856
	1	4.5973	9.3682
	2	3.8831	8.8300
	3	3.5135	8.4214
	5	3.3946	8.0384
500 MCM	0	12.5076	9.9575
	1	4.5496	9.1528
	2	3.8379	8.6245
	3	3.4692	8.2226
	5	3.3479	7.8336

Table A.6 Double Vertical Circuit With Three OHGW Unbalance Data

Conductor Size In MCM	Strand		Per-Cent Sequence Unbalance	
	Al	St	Zero	Negative
1 590 000	54	19	3.5722	8.6805
1 510 000	54	19	3.5672	8.6582
1 431 000	54	19	3.5604	8.6330
1 351 000	54	19	3.5548	8.6079
1 272 000	54	19	3.5490	8.5825
1 192 000	54	19	3.5428	8.5548
1 133 000	54	19	3.5369	8.5239
1 033 000	54	7	3.5295	8.4915
954 000	54	7	3.5216	8.4563
900 000	54	7	3.5140	8.4351
874 000	54	7	3.5135	8.4214
795 000	54	7	3.5031	8.3808
795 000	26	7	3.5070	8.3929
795 000	30	19	3.5124	8.4162
715 000	54	7	3.4923	8.3379
715 000	26	7	3.4968	8.3484
715 000	30	19	3.5013	8.3708
666 600	54	7	3.4874	8.3080
636 000	54	7	3.4827	8.2880
636 000	26	7	3.4846	8.3008
636 000	30	19	3.4910	8.3236
605 000	54	7	3.4771	8.2686
605 000	26	7	3.4808	8.2789
556 000	26	7	3.4728	8.2450
556 000	30	7	3.4771	8.2686
500 000	30	7	3.4693	8.2226
477 000	26	7	3.4577	8.1853

Table A.7 Double Vertical Circuit With Five OHGW Unbalance Data

Conductor Size In MCM	Strand		Per-Cent Sequence Unbalance	
	Al	St	Zero	Negative
1 590 000	54	19	3.4556	8.2745
1 510 000	54	19	3.4503	8.2529
1 431 000	54	19	3.4434	8.2287
1 351 000	54	19	3.4375	8.2046
1 272 000	54	19	3.4315	8.1801
1 192 000	54	19	3.4249	8.1535
1 133 000	54	19	3.4185	8.1237
1 033 000	54	7	3.4108	8.0925
954 000	54	7	3.4024	8.0586
900 000	54	7	3.3946	8.0384
874 000	54	7	3.3940	8.0250
795 000	54	7	3.3833	7.9860
795 000	26	7	3.3872	7.9976
795 000	30	19	3.3928	8.0201
715 000	54	7	3.3739	7.9447
715 000	26	7	3.3764	7.9458
715 000	30	19	3.3814	7.9763
666 600	54	7	3.3666	7.9159
636 000	54	7	3.3618	7.8966
636 000	26	7	3.3639	7.9090
636 000	30	19	3.3704	7.9309
605 000	54	7	3.3561	7.8780
605 000	26	7	3.3600	7.8879
556 000	26	7	3.3513	7.8554
556 000	30	7	3.3561	7.8780
500 000	30	7	3.3479	7.8336
477 000	26	7	3.3357	7.7979

Table 4.8 Ground Wire Effect For Three Arbitrary Sizes (Vertical)

MCM Size	Number Grounds	Per-Cent Sequence Unbalance: Zero	Per-Cent Sequence Unbalance: Negative
1590 MCM	0	4.1629	7.4193
	1	1.0342	7.0572
	2	1.5781	6.6018
	3	1.4674	6.5949
	5	.8197	6.5857
874 MCM	0	4.0261	7.1983
	1	1.0483	7.2249
	2	1.601[illegible]	6.7601
	3	1.4902	6.7534
	5	.8331	6.7440
500 MCM	0	3.9234	7.0314
	1	1.0667	7.4472
	2	1.6313	6.9701
	3	1.5198	6.9636
	5	.8507	6.9539

The undersigned, appointed by the Dean of the Graduate Faculty, have examined a thesis entitled

Electrostatic Unbalances of Transmission Lines

presented by Joseph Nowikowski

a candidate for the degree of Masters of Science

and hereby certify that in their opinion it is worthy of acceptance.

Dr. Turan Gonen

Dr. James R. Tudor

Dr. William Miller

END

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